Metropolitan Comfort: Biomimetic interpretation of hygroscopic botanical mechanisms into a smart textile for the management of physiological discomfort during urban travel.

Veronika Kapsali
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University of Bath
Department of Mechanical Engineering
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Abstract

This project investigates the experience of physiological discomfort during travel through an urban environment such as London or New York in winter. The over and underground networks that lace a current metropolis, form vital passages that lead the traveller though a multitude of spaces each defined by unique temperature, humidity and activity level. It is impossible to predict possible eventualities and consequently accommodate in a selection of clothing to ensure physiological comfort.

Modular clothing assemblies are currently employed for the management of physiological comfort to adjust the insulation and ventilation properties of a clothing system and rely on combinations of behavioural methods and textile properties. This method is compromised by factors such as limited availability of space and wearer’s ability to detect and respond to the onset of discomfort sensations.

Current smart systems rely on temperature as a stimulus for actuation. Experimental work suggests that humidity is a more suitable trigger. Botanical mechanisms that employ hygroscopic expansion/contraction for seed and spore deployment were identified as paradigms for the development of a smart textile system.

Biomimetic analysis of these natural mechanisms inspired the design of a textile prototype able to adapt its water vapour resistance in response to humidity changes in the microclimate of the clothing system. The resulting structure decreases its permeability to air by 20% gradually as relative humidity increases from 60% to 90%.

Acknowledgements

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Chapter 1: The technology and role of physiological comfort in clothing functionality

The relationship between clothing and comfort sensation is a vast and complex subject as it involves both physiological and psychological dimensions. During the last two centuries social, economic, political and technological developments have honed the functionality of clothing and what it means to feel ‘comfortable’ in one’s attire.

1.1 Comfort and the functionality of clothing

The fundamental role of clothing is to satisfy both psychological and physiological needs of the wearer independent of culture, time and activity. These motives were originally identified in the 1930’s as decoration, protection and modesty by English academic psychologist John Flügel. Although it is unclear whether it was psychological or physiological pressures that drove the invention of the first clothing (Flügel, 1971, Ryder, 2000), there is no doubt that the two are inextricably linked.

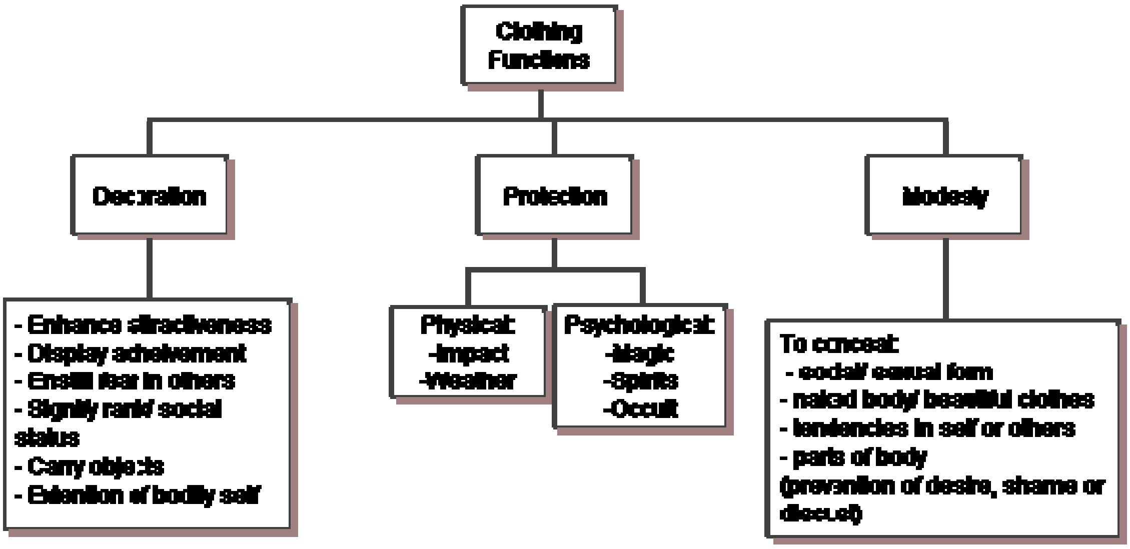

Figure 1: Map of clothing functionality (source: Flügel, 1971)

Figure 1 illustrates the complex nature of clothing functionality but is by no means exhaustive; this study is concerned only with the physiological functionality and in particular the factors that affect comfort, so for purposes of simplicity I will not reference work conducted in the psychological sector.

1.1.1 Physiological comfort

The sensation of comfort from clothing was the subject of great debate (Renbourn, 1971, Kemp, 1971, Greenwood, 1971) among the textile sectors in the 1970's; its vague nature made it impossible to define. It was, however, agreed that there are both psychological and physiological dimensions to the experience (Slater, 1977).

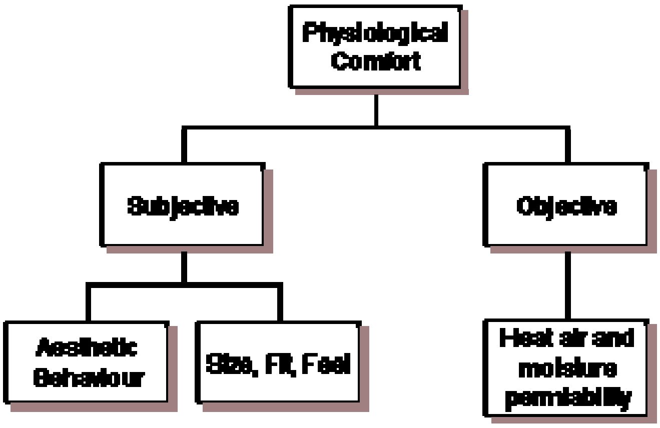

Figure 2: Physiological comfort: effect of textile properties (source Slater, 1977)

Physiological comfort, which is the focus of this study, is further defined by both objective and subjective factors as illustrated in figure 2. The subjective factors include the size, fit and aesthetic behaviour of the garment such as drape[1]. The objective aspect is defined by the garment's performance in relation to the external conditions and activity of the wearer and particularly the clothing's permeability to heat, moisture and air (Slater, 1977).

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[1] Drape: the ability of a fabric to hand in graceful folds (Denton and Daniels, 2002)

1.1.2 Requirements of a clothing system

A system of clothing can be made of one or more layers (base, mid, external) providing a portable environment (Watkins, 1995) of fibrous material and air extending from the surface of the skin to the outer face of the external garment. The role of the system is to satisfy the physiological and psychological needs (outlined in section 1.1.1) necessary for the individual to function within the physical and social environment. A dynamic micro-climate is created within the system and is influenced by external factors (climate, activity of wearer, etc.) and internal factors (fibre properties, textile structure, design of garment, etc)(Black et al., 2005).

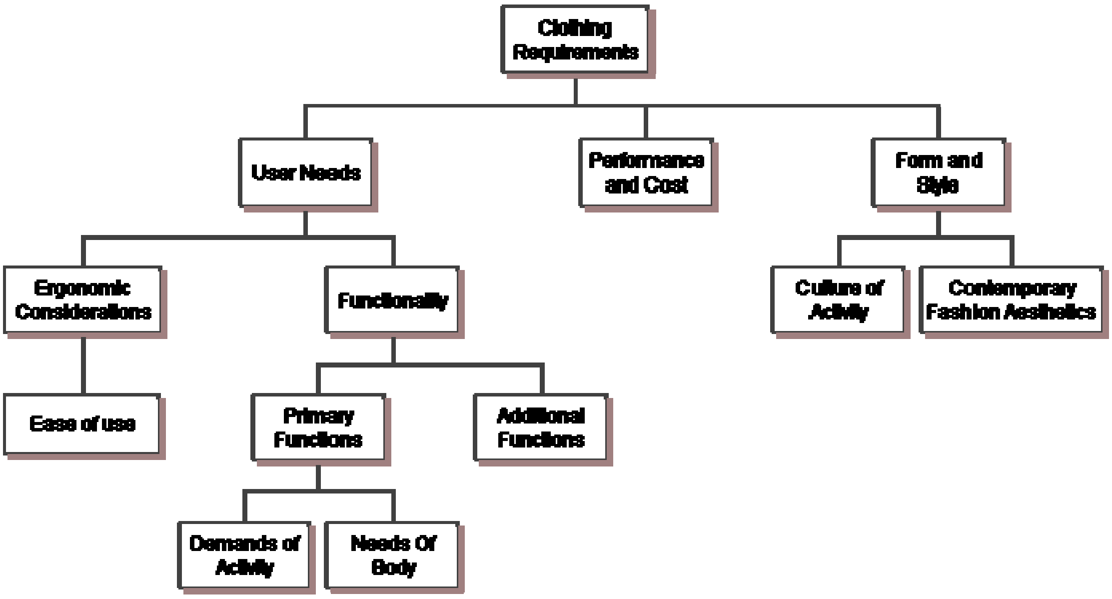

Figure 3: Functional requirements of clothing (Black et al., 2005)

The end use of the clothing system dictates whether emphasis during the design and development is placed on the physiological or psychological functionality of the clothing, however all garments must satisfy some basic requirements (fig 3). The form and style of each item within a system must suit the culture of the activity and meet basic contemporary design aesthetics. Although this may appear more important to the fashion sector, Black (2005) identified several cases where individuals working in hazardous environments rejected their protective clothing because they were deemed unsuitable in terms of look and design.

Clothing needs to balance performance with cost; a successful design convinces the consumer that its price is suitable to the performance of the garment. Clothing must also satisfy basic ergonomic considerations to avoid inhibiting general life activities and functions. It is vital that a clothing system is easy to use (adding and removing garments) and does not restrict movement.

Fire fighters require their clothing to protect them from flames yet prevent them from overheating when exposed to extremely high temperatures and the metabolic heat produced during activity. Cold water diving suits need to sustain the core temperature of the wearer to prevent hypothermia. Urban dwellers in cities such as London or New York require insulating coats and jackets that protect them from exposure to short periods of cold experienced during the winter months. These items of clothing also need to be light and durable and easily removed when they are within an enclosed environment such as a public transport system, place of work or residence.

Additional functional requirements represent possible future demands from clothing enabled by new and emerging technologies. The advancing fields of bio-, nano-, electro- textiles are introducing new properties to apparel that could supplement the functionality of conventional clothing to meet changing needs of the consumer’s lifestyle. Remote connectivity, for instance, enabled by innovations in wearable electronics, offers clothing able to take on additional roles currently performed by devices such as mobile phones, PDA’s and satellite tracking devices. This sector of the clothing industry is very new and the first innovations, pioneered mainly by the sportswear and performance sectors, have begun to appear on the mass market.

1.2 Factors effecting the role of physiological comfort

The literature review revealed that the history of sensory experience from clothing and in particular physiological comfort has never been documented, it also suggests that role of physiological comfort and consumer expectations in Western dress from the Victorian era to the present is honed through social, political and technological pressures.

1.2.1 Physiological comfort in the Victorian era

The clothing of wealthy Victorian men and women included tight corsets, stiff collars, cuffs and multiple layers of heavy cloth that heavily restricted the mobility of the wearer (Newton, 1974). These cumbersome systems functioned as a symbol of wealth and status, the individual was not required to participate in any strenuous physical activities as these tasks were performed on their behalf by staff who were part of the lower classes (Cunnington, 1990).

A lady in Victorian times felt comfortable in her clothing when she was admired for her physical appearance by peers. The female silhouette and in particular the shape of a lady’s waist was of key importance to the overall appearance. Designer corsets ensured highly desirable tiny waistlines; this was especially evident in the advertising of the time. Various corset brands would promote their designs by combining before and after imagery in their promotional material. The before images would usually display women complaining about how ugly and unhappy they felt in their old corsets. These would be followed by imagery of the female stating how comfortable and happy she felt after she had replaced her old corset with a new one because of all the complements she received from her peers (Steele, 1999).

Comfort in Victorian times held a very different meaning to the one we know today. There was no distinction between the physiological and psychological dimensions of the sensation and value was placed solely on the symbolic/

decorative role of clothing. There was in fact no knowledge of the physiological effects of textile and garments on the body until the mid 1800’s where a movement known as the ‘dress reform’ or ‘rational dress movement’ (Newton, 1974) exposed the health hazards directly associated with upper class Victorian dress.

Emily King (a member of the Rational Dress Society founded in 1881) published ‘Rational Dress or the Dress of Women and Savages’ in 1882. The work examined the physical damage caused by body mutilation practiced in Africa (tattoos and scaring) and China (foot restriction) and drew parallels to the use of corsetry which was found to cause permanent disfiguration to female bone structure and vital organs.

The physiological impact of civilian clothing was brought to the attention of the public for the first time in an attempt to improve the individual’s experience of clothing wear. The rational dress movement scrutinised dress etiquette of both western and eastern cultures and exposed factors that threatened the health and wellbeing of the wearer. Emily King revealed the true price of a ‘beautiful’ silhouette while the work of other dress reformers such as Dr Wilson and Dr Jaeger exposed the deadly effect certain dyes used to colour cloth as their poison could be absorbed through the skin, other significant factors identified were the weight and shape of clothing as they burdened the wearer and restricted movement (Cunningham, 2003).

Ease of movement was a key feature in the dress reform mantra which contradicted the stiff and restrictive nature of upper class dress etiquette. However, it wasn’t till the end of the 19th century that lifestyle changes helped ensure the ‘relaxing’ of Victorian dress. Individuals became increasingly interested in the pursuit of leisure and outdoor adventure, both men and women began to engage in various physical activities such as cycling, tennis and swimming. The new lifestyle demands placed pressure on the existing clothing systems and eventually modifications were introduced that enabled participation in such activities. This shift in clothing functionality meant that garments became more practical; men's shirts for instance, lost their stiff collars and cuffs. Although these changes were originally restricted to the countryside, during the early twentieth century more relaxed clothing styles permeated city wear (Willett and Cunnington, 1981).

1.2.2 Physiological comfort in the 20th Century

Textile technology of the early twentieth century was able to deliver sophisticated clothing functionalities to accommodate an outdoor lifestyle. Complex garment systems were engineered to enable the exploration of extreme and hostile environments. George Mallory and Andrew Irvine set out to climb Mount Everest in 1924, although it is not certain whether they reached the summit or not and the attempt cost them their lives. Originally it was assumed that the climbers died because they lacked specialist skills and equipment. However Mallory's body was discovered in 1999 and his garments were analysed by a team at Lancaster University who found carefully engineered layers of silk cotton and wool using construction methods to ensure optimal insulation and wind proof functionality. The team concluded that the clothing system was very efficient (much lighter than modern equivalent climbing attire) and would not have caused death (Phillips, 2005).

The twentieth century also saw the birth of the man-made fibre industry that altered the functionality of clothing once more. Driven by the age old desire to create artificial silk, Rayon was the first man-made fibre to be commercially produced in 1910. Rayon is a regenerated cellulose fibre made from wood pulp or cotton linters (Cook, 1984a). The fibre was originally extruded into filaments that were smooth, straight and imitated the lustre of silk. Rayon soon became a cheap alternative to silk and took its place in dresses, lingerie and coat linings.

The first synthetic fibre was commercially produced in 1939 by E.I. du Pont de Nemours and Company. Following an extensive research program, the company synthesised a polyamide fibre they branded Nylon. Nylon fibres were long, smooth and offered a silk like handle to textiles but with much superior tensile strength. Prior to the invention of Nylon, silk was the finest fibre available in filament form that was strong enough to be used in sheer, fine denier stockings. Silk stockings were expensive and available exclusively to the rich, however, stockings made from Nylon (known as Nylons) were a fraction of the cost and therefore available to all (Handley, 1999).

By the 1950's more synthetic fibres were commercially produced such as polyester and acrylic. These fibres offered an entirely new set of functionality to clothing. Unlike natural and regenerated fibres[2], synthetic counterparts absorbed nominal quantities of moisture (Cook, 1984a) creating quick drying textiles that require little or no ironing. This presented many new opportunities for the swimwear industry and promised to liberate women from household chores such as ironing and washing (Handley, 1999). Even natural fibres were treated with various resins to imitate the performance of synthetic textiles (Kemp, 1971, Smith, 1993).

Crisis hit the synthetic fibre industry in the 1970's as consumers rejected products made from these materials and sales plummeted. This rejection was believed to be fuelled by consumer perception that synthetic textile products had saturated the market (Handley, 1999) and the nature of the fibres themselves caused a range of new sensations such as clingy, damp, clammy, static and various skin irritations (Kemp, 1971). The hydrophobic nature of synthetic materials that created a revolution in the 1950's was the cause of their demise twenty years later as consumers began to favour the properties of natural fibres over their synthetic counterparts.

The 1970's was a very important time for the textile industry. During this decade great losses were made in the man made fibre sector which drove

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[2] Filament: A fibre formed from a solution of natural polymer or of a chemical derivative of a natural polymer and having the same chemical constitution as the natural polymer from which the solution or derivative was made (Denton and Daniels, 2002)

scholars to unravel the meaning of comfort/ discomfort and technologists to find ways of manipulating the performance of synthetic materials to imitate the properties of natural fibres. By the end of the 20th century synthetic fibres had made a total recovery in the clothing sector and in some cases, synthetic textiles could command higher prices than those made of natural fibres (Handley, 1999).

1.2.3 Physiological comfort in the 21st Century

The functional profile of clothing is undergoing yet another reform. Driven by changes in work patterns/ lifestyle and coupled with the experimental application of technology from other areas such as the medical, aviation and military textiles to clothing. New functionalities are gradually finding applications in commercial clothing which is enabled by innovations in production methods such as 3D construction, digital printing and the use of nanotechnology. As these new properties offer non-conventional roles to garments, the boundaries between clothing and the body are shifting. Textiles in the medical sector, for instance, can be used for drug delivery and are integrated into the body; telemedicine uses items of clothing to monitor a patient’s body functions remotely.

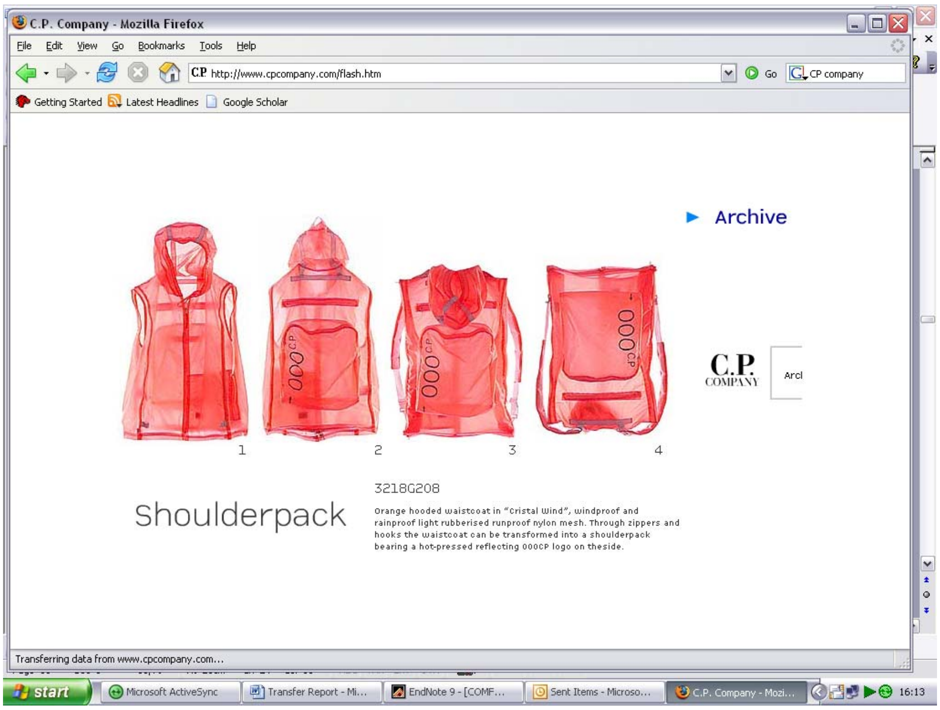
Bolton (2002) reviewed current social and technological trends. The work suggests that some aspects of cutting edge fashion design is tailored to deliver psychological comfort in a modern urban environment (Bolton, 2002). Bolton draws upon the work of Augé (1995), who describes the nature of contemporary urban spaces as busy, transitional spaces or ‘non-places’. Individuals travelling through such spaces do not develop emotional bonds (such as history or memory) with the area and are inflicted with sensations of isolation, confusion and fear (Augé, 1995). The works of the fashion designers reviewed in Bolton’s work develop products to accommodate changes in lifestyle and combat these sensations.

The ‘New Nomad’ is a term coined by Philips Design to describe a lifestyle enabled by portable and wearable technology (Philips, 2000). Devices such as mobile phones and laptops have released some individuals from spending the whole of their working life in a particular place such as an office or studio. Philips took this one step further and developed a range of prototype garments with integrated electronic circuitry that incorporates the functions of a mobile phone, PDA or laptop into that of the clothing system. Other electronic devices that have been incorporated into the structure of clothing are MP3 players, satellite navigations systems and various visual recording devices. These developments are mainly prototypes to illustrate the types of functionality that electronic textile circuitry can introduce to clothing; products have yet to reach the mass market.

The question is do consumers need clothing to perform theses tasks. Bolton’s (2002) work highlights that the needs of individuals alter during the course of any particular day and most current garments do not necessary cater for such requirement changes. The adaptation of the properties of a clothing system is achieved manually by the addition, removal or compression/ extension of items. Modular clothing is a new adaptive concept pioneered by design companies such as Mandarina Duck and C.P. Company (fig 4) who have developed clothing products that can alter their shape, silhouette and functionality by adding/ removing, compressing/ elongating elements to accommodate changing circumstances.

So far, such products command high price tags, are generally considered a novelty or have niche applications (ski jackets, military/ police uniforms). The field of wearable electronics or e-textiles has received heavy investment in the last decade; in fact the market value for Smart Fabrics and Interactive Textiles (SFITs) in 2008 was estimated at US$640M with an annual growth rate of 76% [source: Textile intelligence (2007)], these figures however are inflated because of the large market for heated car seats which use e-textiles and do not represent clothing consumption.

Sensory management is a sub-field of adaptive clothing. Apparel in this category has the ability to manage the wearer's senses in response to psychological or physiological changes in the individual. Dr J. Tillotson [3] has created a prototype garment able to manage the wearer's mental and physical wellbeing by emitting various aromas into the individual's proximate environment. The Woolmark Company have also launched a product that uses microencapsulation to embed various substances into textiles that offer functions such as aromatherapy, insect repellents etc as part of a range branded Sensory Perception Technology ™ [4]. Embedded audio and visual devices also promise sensory management properties to protect the individual from feeling isolated, lonely and provide a protective barrier from the bombardment of audio and visual advertising cues characteristic of 'non-places'.



Shoulderpack

3218G208

Orange hooded waistcoat in "Cristal Wind", windproof and rainproof light rubberised runproof nylon mesh. Through zippers and hooks the waistcoat can be transformed into a shoulderpack bearing a hot-pressed reflecting 000CP logo on theside.

Figure 4: Adaptive modular clothing – a hooded jacket that can transform into a shoulder pack (source: C.P. Company)

Comfort is a key factor in the design requirements of 21st Century clothing. New technologies offer novel methods with which to achieve the desired

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[3] http://www.smartsecondskin.com/main/home.htm
[4] http://www.woolmark.com/services.php?id=89

functionality, however most new developments operate on a psychological platform. This project focuses on the experience of physiological discomfort during travel through an urban environment such as London or New York in winter. The multilayered over and underground networks that lace a modern metropolis form vital passages that lead the traveller though a multitude of natural and artificial spaces each defined by unique conditions (i.e. ambient temperature and humidity) and possibilities (e.g. activity). The plethora of eventualities presented to each individual before embarking on such a journey is impossible to predict and consequently to accommodate in a selection of clothing to ensure physiological comfort. The next section will review current textile technology that aims to enhance comfort relevant to this project.

1.3 The technology of physiological comfort

The physiological comfort of a clothing system is determined by the structure's ability to insulate effectively as well as diffuse excess water vapour emitted from the surface of the skin (see section 1.1.1). Insulation is an important factor in the context of urban travel during winter. The individual however is not likely to be exposed to extreme weather conditions such as those found in the arctic, nor is it likely that the individual would be exposed to cold weather, rain, wind and snow for extended periods. Instead, the urban traveller faces frequent and abrupt changes varying from cold to hot, dry to damp. The type of discomfort experienced in this situation is from inappropriate ventilation and adaptation of the clothing system is often described as clammy or damp.

1.3.1 Sensory perception

Sensation is an important mechanism for living organisms as it provides vital information on the chemical and physical aspects of the surrounding environment (Gescheider, 1997). Cabanac (1979) states that there are two dimensions to the experience of a sensation: discriminative and affective. Discriminative aspect reflects the quantitative (nature) and qualitative (intensity) of the stimuli while the affective dimension refers to the amount of pleasure or displeasure caused by the experience (Cabanac, 1979). Figure 5 illustrates a set of scales representing the affective dimension of sensation according to Cabanac's theory. For purposes of this study modifications have been made to the original wording where the term 'displeasure' has been replaced with 'discomfort'. The term 'comfort' has been also been introduced to the scales to represent a neutral state (Renbourn, 1971).

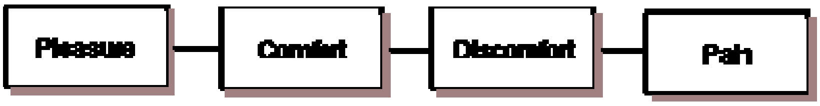

Figure 5: Sensation affective scale

Cabanac's (1979) work suggests that the affective outcome of a stimuli, i.e. whether it instigates pleasure or displeasure, depends on the internal state of the subject; if an individual is hot, physical contact with a cold object would cause pleasure whereas a hot object would cause displeasure. This mechanism is believed to help the individual identify what conditions are required to achieve a type of homeostasis. Sensory pleasure from clothing is unusual, yet not impossible. Flügel (1971) identified certain types of individual that are capable of experiencing sensory pleasure from their clothing. Such individuals demonstrate strong emotional relationships with their apparel and are more sensitive to the psychological aspects of discomfort. The texture of textiles in some extreme cases can elicit sensations of pain to sufferers of Asperger Syndrome[5] or to victims of post-stroke pain syndrome.

The two sensations important to this project are those of temperature and moisture. The mechanism responsible for the detection of temperature in the human skin is well documented. Specialised nerve endings found in the inner layers of the skin are designed to detect either hot or cold. These nerve endings are stimulated by changes in temperature which cause an increase in the impulse frequency. In the case of heat sensitive nerves, an increase in

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[5] Personal correspondence with Bernard Fleming from Research Autism at www.researchautism.net

frequency will be triggered by increase in temperature, similarly a decrease in temperature will stimulate the nerves sensitive to cold (Edholm, 1975).

The sensation of moisture requires a more complex mechanism, Bentley (1900) was the first to identify that there were no direct sensory organs in the skin responsible for the detection of moisture and in fact the nature of the sensation is ‘synthetic’ (Bentley, 1900) meaning that it is generated by a combination of conditions. Experimental work suggested that changes in temperature and pressure at the skin surface created the conditions we perceive as damp or wet. Kerslake (1972) suggested that the perception of dampness is identified through the combined sensation of swelling of the skin from moisture absorption and a change in skin temperature (Kerslake, 1972). While Gagge (1973) found that in a warm environment the sensation is attributed to the increasing strain between two opposing forces: the body’s drive to secrete sweat and the peripheral resistance at the skin’s surface to the expulsion of sweat caused by hydromiosis (reduction of sweat associated by wetting of skin) (Gagge and Gonzales, 1973).

The findings of experimental work conducted by the textile sector aiming to understand the relationship between physiological comfort and the hygroscopic properties of textile fibres reflected aspects of the above theories. It is clear that changes in temperature and pressure at the skin surface create the stimulus humans perceive as damp. Garments made from highly hygroscopic fibres such as wool are conceived as more comfortable than items made from less absorbent fibres such as polyester. Due to their ability to absorb excess moisture into their core, hygroscopic fibres manage the migration of moisture away from the skin (Holcombe and Barnes, 1996) and reduce the vapour pressure in the microclimate (the space between the surface of the individual’s skin and the surface of the external layer of clothing) (Spencer-smith, 1971, Hong et al., 1988, Ha et al., 1999, Scheurell et al., 1995) and thus maintaining positive comfort conditions for a longer period of time

Textiles made from highly hygroscopic fibres are also perceived to be dryer (Li et al., 1992b, Plante et al., 1995a); fibres such as wool demonstrate a lower rate of ambient moisture exchange and maintain higher temperature prior to contact with skin than less hygroscopic textiles. Upon initial contact between the skin and the surface of the textile, Plante et al (1995) noted a drop in temperature, the significance of which was directly related to the sensation of damp or dry. The greater the drop in temperature during initial contact the more damp the fabric was perceived to be.

1.3.2 Product & technology review

Slater (1977) identified that the objective factors governing the performance of a textile system, in this case, is the structure’s permeability to heat, moisture and air (fig 2). Other factors are the activity of the individual and the conditions of the external environment. This section will focus on technology and products that affect the heat, air and moisture permeability properties in the management of clothing microclimate conditions.

The temperature and moisture concentration in a clothing system’s microclimate generates the stimulus that triggers physiological discomfort.
These conditions (temperature and moisture) are greatly affected by the design and the properties of the components that constitute the clothing system.

The product review is indicative and by no means exhaustive. Trade names and companies frequently re-brand therefore names often change. Every effort has been made to ensure that the naming is accurate. Information on the products has been collected from visits to trade fairs (e.g. Premiere Vision) and industry publications (e.g. Techstyle). Although it has not always been possible to obtain technical data supporting the product claims published in the marketing literature due to the protective nature of the industry, every attempt has been made to identify the nature of the mechanisms employed.

Permeability to heat (Insulation)

The thermal performance of a textile or garment is defined by its ability to resist the passage of conductive heat (thermal resistance). It is well known that fibres are generally good but air is a poor conductor of heat. Accordingly, the greater the volume of trapped air within a textile system, the higher its resistance to the passage of heat and the greater insulation it provides. The unit used to measure the insulation value of textiles is tog (1 tog = 0.1 m^2 K/W) or clo (clo = 0.645 togs). The tog is a system developed by the Shirley Institute in the 1960's as a simple alternative to the S.I. m^2K/W. The standard method for measuring the thermal resistance of a textile is by placing a textile sample in between a board with known thermal resistance and 'a cold plate'. The thermal resistance of a clothing system is measured by adding the tog values of the component layers; or by applying the above test to a section of all the fabrics incorporated in the system (Taylor, 1990).

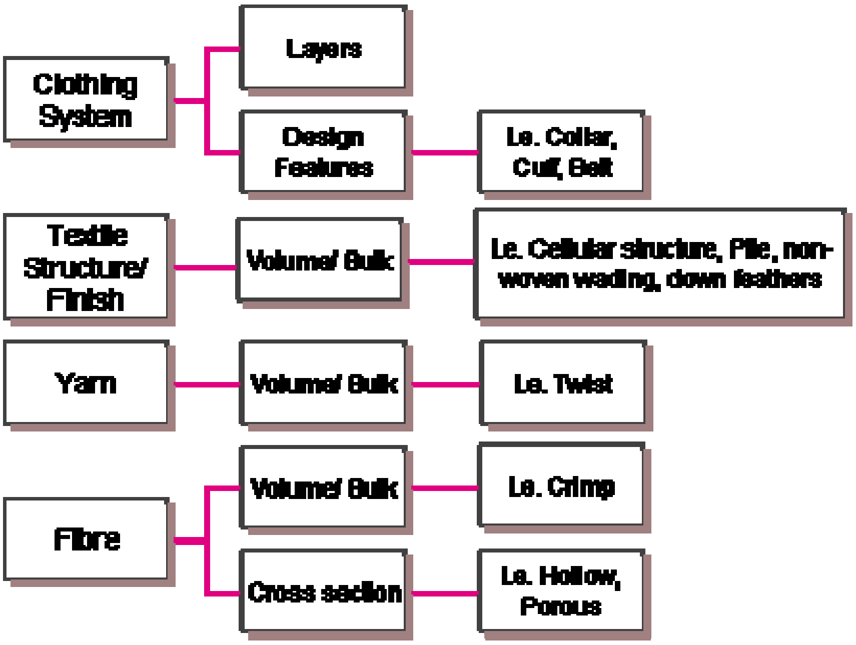

Figure 6: Air trapping methods

There are several methods used to manipulate the insulation properties of textiles, figure 6 illustrates some techniques currently used by the textile industry. It is evident that this property can be engineered into various levels of the hierarchy from fibre to finished garment.

The shape of the fibre is a key factor in the insulation properties of a textile because this influences how closely individual fibres can pack together when spun into a yarn. A wool fibre for instance has a characteristic natural crimp along its length. When packed together into yarns, the crimp structure prevents the fibres from lying close together thus creating pockets of air. Man-made fibres are straight when extruded, but crimp can be introduced at a later stage using bicomponent technology, which will be discussed in greater detail in chapter 5. The cross section of man-made fibres can also be manipulated to increase their capacity to trap air. The design of fibres with hollow cross sections (hollow fibres) is one popular technique which allows for straight fibres to trap greater volumes of air. Thermolite [6] by DuPont and Meryl® Nexten[7] by Nylstar are commercial fibres that use a hollow cross section to improve their insulation properties.

The volume of air trapped within a yarn made from staple fibres [8]can vary depending on the amount of crimp demonstrated by the fibres and/or the amount of twist. Filament yarns can have bulk engineered into them as they are inherently straight. Using the thermoplastic properties of synthetic materials there are a range of methods used such as false twist, knit-deknit, gear crimping, air-jet texturing, etc (Taylor, 1990). Fancy yarns are also quite voluminous, traditional examples are chenille and boucle (Collier and Tortora, 2001).

Volume can be engineered into the structure of a textile using conventional methods such as quilting, cellular knit or weaves, double woven or knitted fabrics all of which introduce additional air pockets into the fabric structure (Humphries, 1996). Advances made in knitting and weaving technology have

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[6] http://www.coolmax-thermolite.com/thermolite.htm
[7] http://www.textileweb.com/product.mvc/Meryl-Nexten-0001
[8] Staple fibres= a fibre of limited and relatively short length (Denton and Daniels, 2002)]

yielded new hi-tech structures; a prime example is the Spacetech product produced by Heathcoat Ltd. Heathcoat have developed a knitting system that creates three dimensional textiles known as spacer fabrics, where a web of interconnecting yarns is engineered to bind two layers of fabric. The distance between the two layers of textile determines the volume of air trapped and in effect the insulation properties.

Pile structures such as velvets, velour and synthetic furs also trap air at the surface of the fabric. Additionally, composite textile structures combine layers of textiles with different properties by bonding them together to produce multifunctional textiles with high insulation values; wadding[9] or feathers are commonly trapped between two layers of fabrics to increase the volume of trapped air. Nap'tural by Naptural SAS[10] produce insulation sheets composed of 60% natural down and/or feather and 40% synthetic fibre whose main application currently is the construction industry.

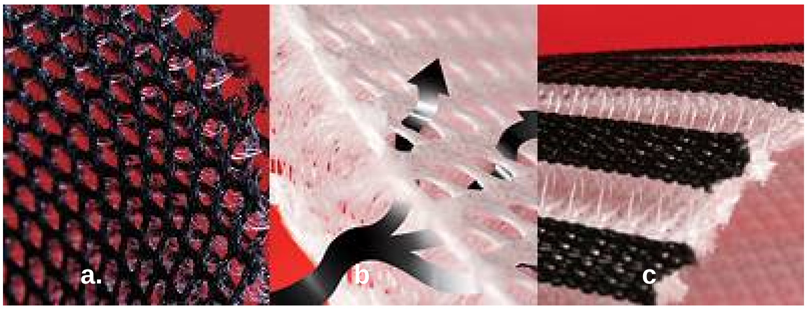

Figure 7: Cross sections of Spacetech textiles by Heathcoat, a and c are two design variations and b illustrates the air flow through the textile.

Composite textiles such as membrane/textiles laminates can manipulate thermal performance by incorporating a metal such as aluminium into the textile system, thereby giving it the ability to reflect heat generated by the body

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[9] Wadding: a lofty sheet of fibres that may be bonded, used for padding (Denton and Daniels, 2002)

[10] http://209.85.227.132/translate_c?hl=en&sl=fr&u=http://www.batiplum.com/index.html&prev=/search%3Fq%3DNaptural%252BSAS%26hl%3Den%26sa%3DG&rurl=translate.google.co.uk&usg=ALkJrhgdh_5bvvY8RnNorYdSCvs0qDSX7g

(Tastuya and Glyn O., 1997). The Reflect' line by HT Concept Diffusion[11] is a textile system comprising of a hydrophobic polyurethane membrane containing aluminium particles laminated onto a textile. Similarly, Sympatex Reflexion[12] by Sympatex Technologies is a non-porous polyester membrane with an aluminium coating; the company claims that their products reflect 75% of infrared radiation emitted by the body.

Indetex claim that their Cool & Fresh textiles draw away from the body heat produced by muscular activity, far-infrared radiation from the sun and environmental heat through the incorporation of Sophista and Lonwave fibres into the face of the fabric and multilayer knit construction. Sophista is a bicomponent fibre made from ethylene vinyl-alcohol and polyester. Lonwave is a polyester staple fibre with a hollow cross section that contains ceramic particles believed to reflect far-infrared rays.

Aerogels are used as an alternative thermal insulator to air; this technology has migrated from the medical industry. Manufactured by Aspen Aerogels Incorporated, this is a nanoporous material that has greater free void volume (<90%) than textiles conventionally used for insulation. This increase in pore volume has been found to produce twice the thermal resistance of air (English, 2003), and five times that of Thinsulate by 3M, which is a well established brand of non-woven microfibre insulation materials used for outdoor clothing and accessories. Water and helium are other media that have also been applied experimentally to the management of heat energy in garments by trapping them into non-porous structures used as garment inserts.

Design and assembly of the garments are structural features that effect the insulation properties of the clothing system. The incorporation of collars, cuffs and belts in the structure of a garment, for instance, encapsulates volumes of air into the microclimate. The layering method is another technique used to manage the amount of trapped air between layers of garments; more clothing

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[11] http://www.htconcept.com/

[12] http://www.sympatex.com/images/uploads/PDFs%20komprimiert/SYM_067_Produktfolder_engl_final_030908.pdf

layers = more warmth. This is currently the most practical technique for the wearer to accommodate changes in activity and external conditions. The individual can put on or take off items of clothing in response to his/her assessment of personal comfort level at any point.

Permeability to moisture

The diffusion of moisture vapour through the matrix of a textile system involves many complex interactions that depend mainly on the chemical composition of the fibre and the structure of the textile. During perspiration, the body uses the evaporation of moisture at the skin surface to cool itself. This moisture is stored in the clothing system's microclimate. Water molecules penetrate the textile matrix and can interact with it in a variety of ways: they can stick to the surface of the fibres, penetrate the core and/ or congregate in the capillary spaces created between fibres. Water molecules can also migrate from the interior of the system to the surface where they evaporate into the atmosphere.

When moisture builds up high concentrations in the microclimate of a clothing system, it condenses into water droplets. This is directly associated with sensations of discomfort and in particular a sensation described as damp or clammy (Gagge and Gonzales, 1973, Plante et al., 1995a, Li, 2005). Permeability to moisture is measured in terms of water vapour resistance. The lower the vapour resistance of a particular textile the more comfortable the textile is considered to be (Taylor 1990). Textile systems with high vapour resistance properties prevent the diffusion of moisture through the fabric resulting in the development of a high concentration of moisture in the microclimate. It is therefore important for a system to maintain low moisture content in the microclimate.

There are several methods used to measure the water vapour resistance of a textile; each uses a different apparatus but all generate a value through the measurement of latent mass change in a textile that has been subjected to high humidity conditions. The main unit used to measure water vapour resistance is g/24h/m^2. A comparative study of these methods was conducted by McCulloch et al (2003), who found that same fabrics ranked differently in the various test and each method is relevant to a particular range of textile construction, however companies often use the method that yields the most favourable results for a particular product.

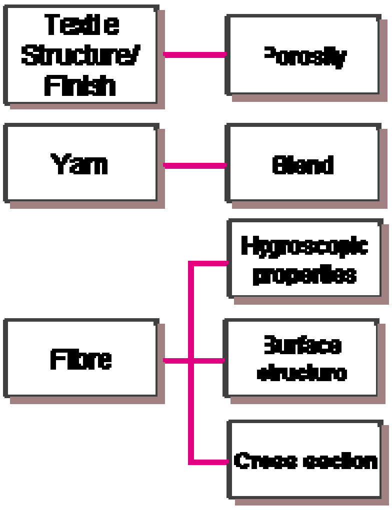

Figure 8: Moisture diffusion methods applied at various levels of hierarchy. Structure porosity affects the passage of air through the textile; yarn blend refers to the combination of fibres used to create the yarn. Natures of fibres plays significant role main factors are hygroscopic properties (a hygroscopic fibre allows penetration of moisture), can moisture adhere to the surface of the fibre, this is influenced by the structure of the fibre surface. The shape of the cross section effects the amount of moisture that can attach onto the surface of the fibre.

A key term often used in marketing literature to describe the water vapour resistance properties of a textile is *breathable*, which refers to a fabric that offers high resistance to liquid water yet low resistance to water vapour (Denton and Daniels 2002). This term is frequently used in the marketing of composite textiles used in outer layer garments especially when one component is a membrane. Another is the *wicking* properties of a fibre or fabric which describe the rate at which the absorbed moisture is dispersed across the volume of the textile and is driven by capillary forces (Denton and Daniels 2002). The term is often used in the marketing to describe a textile's ability to draw moisture away from the skin, sometimes to the face of a textile where it evaporates into the atmosphere.

Similar to the management of heat movement within a textile system discussed in the previous section, there are several factors that affect the moisture diffusion properties of a textile as illustrated in figure 8. The various mechanisms involved are highly complex and have been studied in great detail (Spencer-Smith, 1977, Gibson and Pan, 2006, Li, 2001), this section will provide a simplified overview of the key factors.

The hygroscopic properties (how readily they absorb moisture into their core) of fibres is possibly the most significant contributor the moisture diffusion performance of a textile and in effect the sensation of comfort. As discussed in section 1.3.1 garments made from highly hygroscopic fibres are perceived to be dryer and more comfortable than their less absorbent counterparts. Hygroscopic fibres also attribute a ‘buffering effect’ to clothing that improves the comfort of the wearer during transition from a dry environment to a damp one. It was found that the fibres absorb excess moisture delaying the sensation of damp by the wearer. Accordingly, when stepping from damp to a dry environment, the moisture in the fibres is released and the wearer experiences a cooling sensation (Dear et al., 1989, Li et al., 1992a).

Hygroscopic behaviour is affected by the alignment of molecules in the fibre. Fibres are made up of a combination of crystalline and amorphous regions; the ratios vary depending on the type of fibre. Water can penetrate only the amorphous areas because the molecules in the crystalline sections are bound tightly together by chemical bonds (Cook 1984). Natural and regenerated fibres have high ratios of amorphous regions compared to their synthetic counterparts, this is due to the stretching processes the filaments (fibre of indefinite length) are exposed to during manufacture which creates greater areas of aligned molecules (Latta 1977).

The nature of the fibre surface can encourage or discourage the adhesion of water molecules. In the first case, the fibre is classified as hydrophilic and associated with comfort. Natural and regenerated fibres fall into this category. The latter are known as hydrophobic and are generally considered uncomfortable. Synthetic fibres are hydrophobic by nature despite the presence of hydrophilic monomers in their polymer chains because they are submerged into the layers of the fibre skin during manufacture. Other contributing factors to the hydrophobicity of synthetic fibres are the smooth surface and lack of bulk generated in the filament yarns (Latta 1977). Coolest Comfort by Nano-Tex and Intera by Intera Corporation both use nanotechnology to mask the hydrophobicity of synthetic fibres by grafting hydrophilic groups to the surface of the fibre.

The commercialisation of microfibre technology in the 1990's demonstrated that structures made of synthetic fibres could be breathable. Due to their fine structure, which is less than 1 denier (the mass in grams of 9000m of a fibre, filament or yarn), tiny holes are created between the fibres when spun into a yarn and constructed into a textile, they allow the passage of water vapour, therefore creating a breathable structure e.g. Micro Supplex by Invista[13].

Hydrophobic properties enable textiles to achieve rapid capillary wicking rates, meaning that they dry quicker. This can be further improved by manipulating the cross section of a fibre to increase the overall surface area which in turn results in even quicker evaporation of the excess moisture (Patnaik et al., 2006). DuPont's Coolmax[14] range employs this method, made from a hydrophobic copolymer; the cross section has 4 grooves running along the length of the fibre revealing a cross section often referred to as 'Mickey Mouse ears'. This is believed to increase the surface area of the fibre by 20% compared to a standard round cross section. Similarly, Technofine[15] by Asahi

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[13] http://www.invista.com/page_product_supplex_en.shtml
[14] http://www.coolmax-thermolite.com/coolmax.htm
[15] http://www.asahi-kasei.co.jp/fibers/en/r_technofine01.html

Kasei have developed a w-shaped cross section. Another fibre that uses cross section design to increase wicking is Becool[16] by Condamin et Prodon

Textiles made from hygroscopic fibres such as cotton and viscose (rayon) help maintain lower vapour pressure in the microclimate by absorbing moisture into their core. However, once saturated these textiles become very uncomfortable and difficult to dry when compared to their synthetic counterparts. It is possible to combine the positive properties of the two fibre types and minimize negative effects by blending natural or regenerated with synthetic fibres in a yarn. Sportwool by the Woolmark Company uses yarns composed of both wool and synthetic fibres whose functionality and comfort properties have been found to surpass those of cotton in base layer garments such as T-shirts (Holme, 2003).

The density of a textile structure can play a significant role in the diffusion of moisture but the nature of the fibres is the key factor. Fort and Harris (1947) conducted a comparative study of a range of natural, regenerated[17] and synthetic textiles; the findings revealed that diffusion occurs in textiles made from either natural or regenerated fibres in spite of the density of the structure. Synthetic fibres, however, increase their vapour resistance in denser structures. The hygroscopic properties of natural and regenerated fibres allow the moisture to be drawn into the fibre whereas textiles made from synthetic fibres rely solely on capillary wicking to diffuse moisture which only occurs in higher humidities (Adler and Walsh, 1984).

Perseverance Mills have developed a woven textile called Pertex[18] that controls the direction of the water vapour diffusion by using a denier gradient structure. Thicker polyamide yarns are engineered into the inside of the weave while the face of the fabric is made of microfibres; this is claimed[19] to draw moisture from

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[16] http://www.lsmalhas.com/becool_video.html

[17] A fibre formed from a solution of a natural polymer or of a chemical derivative of a natural polymer and having the same chemical constitution as the natural polymer from which the solution or derivative was made (source: Textile terms and definitions, 11th edition)

[18] http://www.pertex.com/main.php

[19] http://www.pertex.com/main.php

the microclimate to the surface of the garment. 3XDry by Schoeller also demonstrates a similar functionality however; the mechanism includes hydrophobic treatments.

During the 1990's breathable, water resistant membranes and coatings started to find applications in the casual clothing sector. The basic principle supporting this technology is that water in the form of vapour is able to pass through the membrane whereas drops are not. There are two types of products available, the first is expanded PTFE whose surface is characterised by micropores permeable to water vapour, Goretex by Gore and Associates were the first to develop this technology[20]. The second type is known as a hydrophilic/phobic membrane and was originally developed by Sympatex Technologies[21]. The hydrophilic side of the membrane faces the interior of the clothing system and draws the moisture away from the skin toward the surface of the textile, while the hydrophobic layer prevents moisture in the form of droplets from entering the system. Several variations of these have been developed over the years but operate on the same principles.

Permeability to air (Ventilation)

Fibre hygroscopicity and good moisture diffusion can help maintain steady vapour pressure in the microclimate when excess moisture is introduced, the enclosed air will eventually become saturated thus eliciting discomfort sensations. In order to prolong or prevent this it is necessary to replenish the air trapped in the clothing system. This can be instigated by the wearer with the aid of design features and/or by the properties of the textiles. The key factors affecting the permeability of a textile to air are the thickness and porosity of the structure. The shape of the fibre (amount of crimp) can contribute to these properties but it is the yarn and textile structure that play the most significant role in this aspect of textile performance (Kullman et al., 1981, Backer, 1951).

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[20] http://www.gore.com/en_xx/aboutus/index.html
[21] http://www.sympatex.com/

Periodic ventilation is the main method used to manually manage air renewal in the microclimate. Ancient Inuit clothing was made of insulating and waterproof furs and feather pelts yet the garment's design enabled extremely efficient ventilation (Ammitzboll et al., 1991, Humphries, 1996). The traditional Inuit hood was closely fitted around the face with no front opening and air was trapped in the system at the chin and waist. The sleeves on the parka were long enough to cover the hands and fitted to prevent cold wind from penetrating the system. During periods of activity when the microclimate was threatened by saturation, ventilation was achieved by pulling the garment forward at the front of the throat, pushing the hood back or loosening the closure at the waist (Humphries, 1996). Conventional clothing uses design features such as zips and openings to enable the renewal of saturated air in the microclimate (Ruckman et al., 1999).

The physical factors affecting the permeability of textiles will be discussed in greater detail in chapter 5. As a rule of thumb, fabrics that demonstrate firm texture, close structure and short floats (e.g. plain weave) are generally less permeable to air. Whereas open structured, fine fabrics with long floats (e.g. sateen weave) demonstrate higher permeability. Various finishing processes can also effect the performance of a textile (Schiefer et al., 1933).

Textiles with low air permeability are important for use in clothing systems designed for cold weather conditions as they keep warm air in and prevent cold air from penetrating the system. However, physiological comfort depends on the system's ability to adapt its permeability properties in accordance to changes in the wearer's activity. Even clothing designed for extreme cold conditions must take this into account, which is why the Inuit system is a successful example. Textiles with high air permeability are used for clothing systems designed for hot weather climates because they allow for constant air renewal necessary when the individual is sweating regardless of activity levels.

Wind resistance

Tightly woven structures, felting/ milling techniques, and natural skins were traditional methods used for protection against wind and cold. Today, advances in knitting technology coupled with the development of microfibres, have enabled the production of tightly knitted fleece structures such as Polartec Wind Pro[22] by Malden Mills which is a 100% polyester fleece whose tight knit construction increases its resistance to wind penetration.

Wind resistant membranes or coatings are commonly incorporated into a composite textile system to offer a host of functionalities. Sympatex Windmaster[23] by Sympatex Technologies is a 100% polyester membrane with aluminium which reflects body heat and increases wind resistance. Windstopper Soft Shell[24] by Gore & Associates is made of an expanded PTFE membrane designed to act as a barrier against wind when combined with fleece or other materials.

1.3.3 Adaptive/ smart technology

Conventional clothing systems rely on wearer intervention to adapt insulation and ventilation properties of a garment system. Consumer trends suggest that expectations from apparel are changing and that individuals may require their clothing in the future to alter its functionality without the wearer's intervention (see section 1.2.3). The textile industry is currently seeking systems that offer alternative methods of adapting the performance of a clothing system; this section will review key commercially available developments.

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[22] http://www.polartec.com/contentmgr/showdetails.php/id/214

[23] http://www.sympatex.com/technologien/produktlinien/sympatex_windmaster

[24] http://www.windstopper.co.uk/remote/Satellite?c=fabrics_cont_land_c&childpagename=windstopper_en_GB%2Ffabrics_cont_land_c%2FTechnologyOfComfortFrameset&cid=1151345853519&p=1151345855441&pagename=SessionWrapper

The manipulation of insulation properties through the control of the volume of trapped air in a clothing system is known as Variable Geometry. Some development has been carried out by N. & M.A. Saville Associates (fig 9). The structure consists of two layers of fabric, which are joined together by strips of textile at a vertical angle to the plane of the two fabrics. By skewing the parallel layers the volume of air between them reduces. This results in the reduction of the insulation value. The idea was used in the design of military uniform systems that can be adapted to function in both extreme cold and hot conditions. This product is still in development; however Alex Soza (fig 10) developed the *Bionic Jacket* concept. This design employs the principles of variable geometry for the manipulation of insulation values but the mechanism is incorporated into the shape of the garment and not isolated to the textile system.

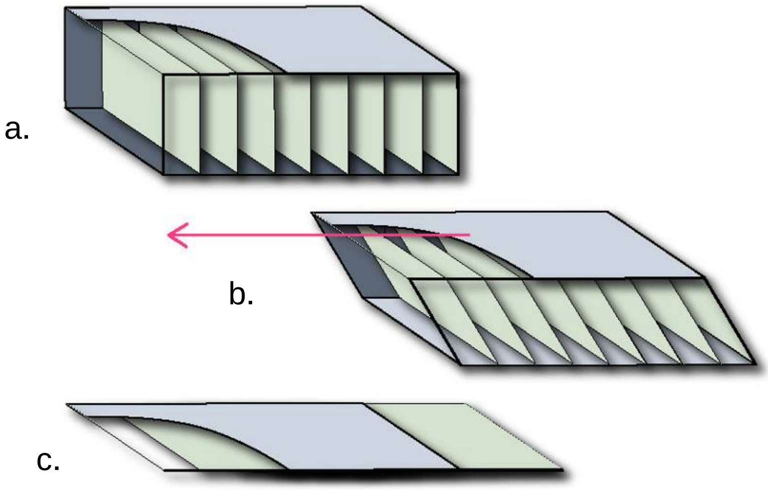

Figure 9: Variable geometry concept (source: N. & M.A. Saville Associates). Textile system comprising of two layers joined together by textile strips at 90° angles. 9a. Configuration allowing the maximum volume of trapped air between top and bottom layers thus providing maximum insulation. 9b. By skewing system volume of trapped air is reduced. 9c. System fully compressed trapping the minimum volume of air.

A commercial version of this concept is Airvantage by Gore & Associates. This adaptive insulation mechanism allows the wearer to adjust the volume of trapped air, thus managing the heat resistance of the garment. In the form of an inflatable lining insert, the structure is made from two layers of expanded polytetrafluoroethylene (ePTFE) membrane and polyester membranes (76%PE 24%PTFE) that are bonded together at points that form a network of tubes (fig 11); this product allows the user to inflate/deflate the jacket thus controlling the necessary amount of air for the provision of adequate thermal resistance.

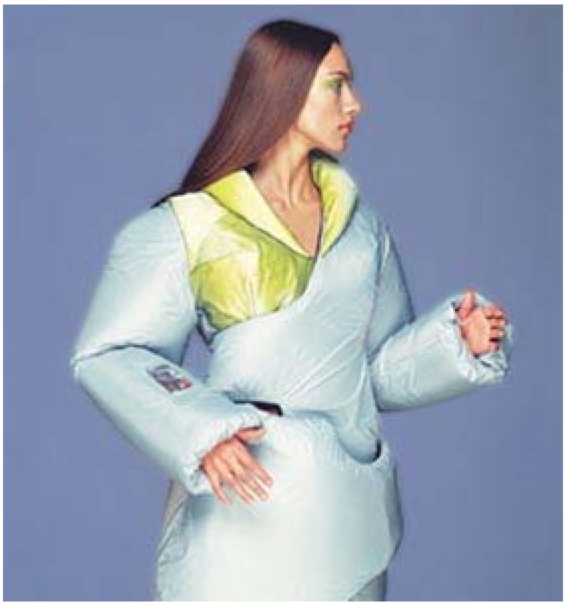

Figure 10: Bionic Jacket: Image shows jacket in inflated state, inflation is managed by integrated control pad on sleeve (left). (source: Alex Soza)

Shape memory polymer (SMP) membranes are the main technology used to introduce adaptive moisture vapour resistance properties to clothing. Mitsubishi Industries originally developed a smart membrane branded Diaplex[25] in the 1990's. Recently Schoeller launched a product into the European market that uses a similar membrane technology under the brand C-change[26]. According to the marketing literature the mechanism that enables this functionality is based on micro-Brownian movement which is a temperature related phenomenon. At lower temperatures the molecules in the membrane obstruct the diffusion of air

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[25] http://www.diaplex.com/

[26] http://www.schoeller-textiles.com/default.asp?cat1ID=128&cat2ID=134&pageID=317&emotionstate=0&emotionID=1&langID=2

and vapour through the membrane and at higher temperatures the bonds loosen enabling the passage of air and moisture. Mitsubishi Industries claim that the temperature at which the functionality change occurs can be engineered into the polymer. These products will be discussed in greater detail in chapter 5.

Figure 11: Jacket lining with Airvantage lining inserts (source: Gore and Associates)

Phaseable[27] by Sympatex is a hydrophilic/ phobic membrane lined with a black film that forms the base of the system. The side adjacent to the skin features printed motifs using a foam based substance that swells as it absorbs moisture. Originally printed in triangle shapes, these sections raise the surface of the textile away from the skin and Sympatex claim they pump moisture out of the system. The benefits and nature of the mechanism are unclear from the available literature and Sympatex were unable to disclose any information due to a confidentiality agreement with Nike at the time of this research. It may be

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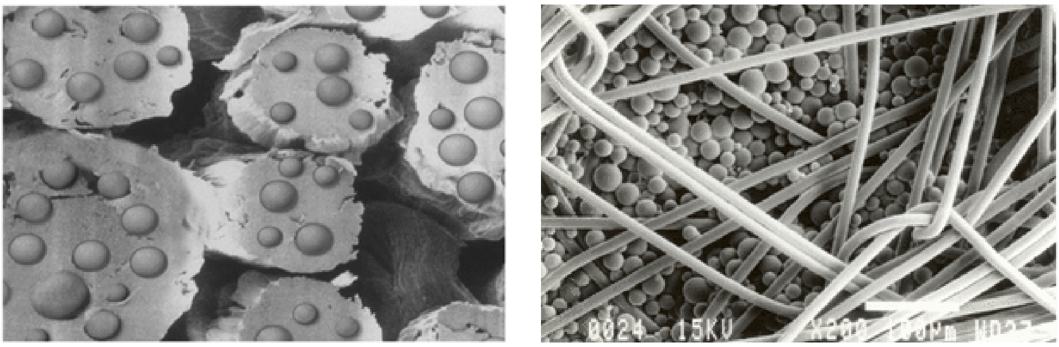
[27] http://www.sympatex.com/technologien/innovationen_2/innovationen_-_sympatex_phaseable_2

that the swelling foam absorbs moisture from the microclimate thus maintaining low vapour pressure for longer.

Phase change microcapsule (PCM) technology has introduced adaptive heat storage/ production properties into clothing. Originally funded by NASA and carried out by Triangle Research Group the technology was intended for use in space applications. Triangle was later renamed Outlast Technologies Inc and focused on applications in the textile and apparel sector. The technology involves the use of tiny ceramic capsules that are filled with paraffin-hydrocarbon which convert to liquid form in warm conditions and solidify in cool conditions. The PCMs can be applied to the textile either directly into the fibre (fig 12a) or as a coating (fig 12b) onto the finished fabric.



a: in fibre

b: in coating

Figure 12: Phase change microcapsules (source: Outlast)

The adaptive nature of the product lies in its phase change mechanism. When the microclimate is hot, the paraffin absorbs the excess energy and stores it as in liquid state; the effect on the wearer is a cooling sensation. When the temperature of the microclimate drops the paraffin releases the heat energy by becoming solid state, thus heating the wearer (Pause, 2003, Holman, 1999).

Conclusion

This chapter has examined the impact that lifestyle and technology have on consumer expectations and the requirements of clothing. It is very likely that clothing of the future will incorporate novel functionalities additional to those of conventional clothing. Already smart and adaptive textile technologies are finding their way to consumers through the garments they purchase, but these are focused on the psychological dimension of clothing functionality. The physiological needs of individuals in urban environments have not received much attention from new developments but are a persisting problem. Modular clothing systems are used to manage physiological discomfort but the problem with these is that they involve adding and removing layers or opening and closing zips and fastenings, this is not always ideal for the individual who may be in transit or in confined space.

The focus on current smart developments pivots around the use of temperature changes as stimuli for adaptation; however there is no data to support the marketing claims. This raises questions on the suitability of temperature as trigger for an adaptive system designed to combat physiological discomfort. The next chapter will review the literature on methods used to link damp sensation with microclimate temperature and humidity and the effect of textile properties, to map existing work and knowledge. This is followed by a description of the design and execution of a trial designed specifically for the identification of ideal stimulus and comfort conditions.

Chapter 2: Physiological discomfort and the role of clothing

Pressures from the changing relationship between the city dweller/ commuter and the nature of urban cityscapes in conjunction with advances in novel technologies are gradually altering consumers' expectations from their apparel. Already clothing systems are available that offer additional, non-conventional functionalities such as remote communication (embedded Bluetooth, GPRS and mobile phone technology) and entertainment (integrated audio equipment).

As a consequence, expectations of conventional properties of clothing are also being driven forward; novel technologies promise to alter the performance of a clothing system to meet the wearer's physiological needs. The product review in the previous chapter showed that current developments in smart and/or adaptive textile technology employ temperature as a stimulus in mechanisms such as latent heat storage (PCM) and variable moisture vapour resistance (SMP membranes). However, it is questionable whether these developments are designed to work in partnership with the microclimate of the wearer (despite claims in the marketing literature) and adapt to the individual's *actual* physiological needs.

Cities such as London or New York are hives of activity whose lifeline is an intricate system of under and over ground transport networks. These networks are composed of many isolated environments whose climatic conditions vary greatly in terms of temperature and moisture. In the winter months, individuals can step from a cold to a hot environment or damp to dry (and opposite in the summer), several times before they reach their destination as well as alter the level of their activity (slow walk to run). Modular clothing and layering assemblies are capable of adjusting their insulation and moisture resistance properties, but this needs to be done manually by the individual by unbuttoning their coat, etc. This method is often compromised by limited availability of space in public transport vehicles and the luggage carried by individuals. Also the wearer's ability to sense the onset of discomfort in time limits his/her success at adapting the properties of the outfit.

2.1 The study and measurement of discomfort from moisture

The combined effects of changes in microclimate temperature and vapour pressure at the skin of the individual cause the physiological discomfort (Bentley, 1900, Plante et al., 1995a) relevant to this project. Until clothing made from synthetic fibres entered the market on a mass scale during the 1960's and 70's, these sensations were virtually unknown. Terms relating to the conventional properties of textiles of the time such as hot, cold, tight, heavy etc failed to reflect the nature of the discomfort consumers were experiencing. (Hollies, 1977) studied this new form of discomfort and noticed that the same sensory descriptors such as clammy, damp and clingy reappeared in numerous independent subjective studies. These terms have since been used by the industry to describe the sensation caused by the concentration of moisture in the microclimate of clothing.

Subjective measurements are a valuable tool for the study of the experience of the wearer, but they can be problematic. Slater (1986) identified that this kind of data usually is inconsistent due to the influence of psychological, physiological, social and environmental factors and rely upon the honesty and subjective opinion of the individual. Subjective trials also produce non-numerical results that are difficult to analyse statistically, while trials that focus on objective factors produce reliable and consistent data (Slater, 1986).

The instruments used to measure the moisture resistance of textiles were discussed in section 1.3.2 and provide information used widely in the textile industry especially for testing industry standards. The numerical data produced can predict the sensory influence of a textile during use (Slater 1986); generally a textile with low resistance to moisture would be more comfortable than one with high resistance.

Other devices imitate the behaviour of human organs such as skin. Holcombe and Barnes (1996) used an apparatus designed to simulate sweating skin to study the impact of fibre hygroscopicity on the migration of moisture vapour. Textiles made from 100% wool and 100% polyester were tested and the results indicated that 30% more moisture is transported from the skin by the wool fabric than the polyester and therefore should be more comfortable. This type of data provides useful information on the performance of a particular textile and how it compares with others, but is not directly linked with the sensory experience of an individual and therefore poses limitations to the purposes of this study.

2.1.1 Psychophysics and moisture sensation

The link between sensation and physical stimulus is enabled through the field of psychophysics which has its origins in the 1860’s and describes the relationship between experience and stimulus (Gescheider, 1997) by measuring the strength of sensory experience. Psychophysics was originally applied to senses such as smell and touch, and the textile industry adopted some of the principles to the study of tactile sensation from textiles and later physiological comfort. Sweeny and Branson (1990a) where the first to demonstrate that psychophysical techniques can be applied to the study of moisture sensation in relation to textile properties (Sweeney and Branson, 1990) and produce reliable results. The mathematical tools of psychophysics are used to quantify the intensity of the stimulus and identify the threshold or the minimum amount of stimulus necessary for the subject to detect a difference. An in depth account can be found in the work of Li (2001). These are not relevant to the purposes of this work and will not be further discussed. It is the scaling techniques that are useful to this study.

In indirect scaling the subjects are asked to compare several pairs of stimuli and place them in order of intensity or on a rank in a scale. Plante et al (1995a) exposed a group of subjects to four types of fabric at different humidities in order to study the effect of fibre hygroscopicity and the perception of damp (Plante et al., 1995b). A scoring scale was used to rank the perceived dampness of each textile. Fabrics made from highly hygroscopic fibres such as wool felt drier than those made from polyester.

Direct scaling requires the subject to make estimates of the stimuli's sensory magnitude with reference to a standard value. Sweeny and Branson (1990b) used a 50/50 blend of polyester and cotton single jersey textile swatches that contained different amounts of moisture (Sweeney and Branston, 1990). Subjects were asked to assign numbers to each sample that reflected the amount of moisture perceived in the textile.

Psychological scaling is another technique used to link sensations with numerical values. Although there are several different types, the scales used to study comfort, function as measures of attitude[28] (Li, 2001). Attitude scales were pioneered by Hollies et al (1979) as part of a method developed to analyse human perception where subjects were asked to rate the intensity of sensations from a list given to them during the trial (Hollies, 1979). Li et al (1992) developed subjective rating scales to measure clamminess and thermal sensations in order to study the moisture buffering behaviour of hygroscopic fabrics (Li et al., 1992b) and further developed this tool (fig 13) to include perceived comfort (Li, 2005).

2.1.2 Psychophysical methods applied to clothing microclimate

Studies employing psychophysical methods for the investigation of moisture sensation have focused exclusively on various specific locations such as areas of skin on the back and inner forearm. The most relevant study by Li (2005), conducted a series of trials to study the perception of moisture and temperature from the clothing system and the relationship to comfort. Focusing on the microclimate, the data included subjective measurements of comfort (thermal

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[28] The way in which the individual feels in response to a trigger

and moisture sensations) which were recorded using psychological rating scales illustrated in fig 13, while objective data on the temperature and moisture content of the microclimate was recorded simultaneously.

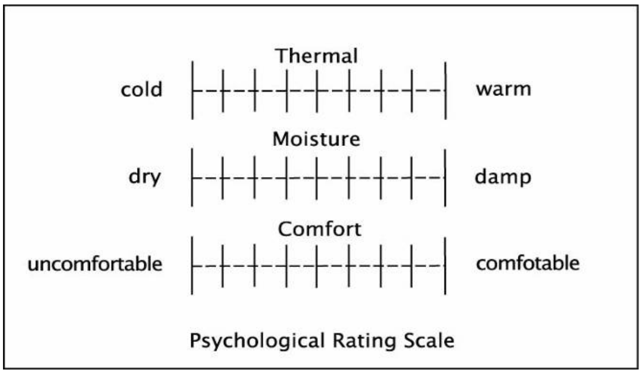


Figure 13: Subjective rating scales (Source Li ,2005)

The trials were conducted in a controlled environment of 20^{O}C and 80% RH; rain simulations were included in the protocol. The subjects felt comfortable, warm and dry when $T_{skin} > 34.4$ ^{o}C. Uncomfortable and damp sensations occurred around $T_{skin} = 34$ ^{o}C. The subjects also felt a sharp increase in the sensation of dampness and decrease in comfort around 50-55% relative humidity. Although the work of Li (2005) was not designed to identify the boundaries of comfort in the given climatic conditions, valuable information has been extracted from the work.

This project further explores the sensation of discomfort using inexpensive and non-lab based methods to pilot the study of the physiological comfort threshold in a cold and dry environment and distinguish between temperature and moisture for the stimulus most representative of the onset of clammy/ damp sensations.

2.2 Experimental trials: The Journey

The Journey is a name coined to describe the process of data collection designed to identify the changes in microclimate temperature and moisture content that trigger the sensation of discomfort during ‘real time’ urban travel.

This was achieved through the simultaneous collection of both subjective and objective data in a real environment and the subsequent analysis of their relationship.

The work began in October 2003 and evolved over two phases, the second building and improving on the first. The first stage was speculative and occurred before any review of literature had been conducted. A single thermocouple with two sensors was used to measure skin and external temperatures and the subjective data was recorded in a note book noting the time with a stopwatch that had been synchronised with the thermocouple's clock. The timeline functioned as a link between sensation and actual skin temperature. During the analysis of the data, it became apparent that the findings were not representative of the sensations experienced. Temperature measurements alone did not provide an accurate representation of the microclimate conditions.

This stage also helped develop the method and protocol of the final trials; it became apparent that the language used needed refining and that a set of sensory descriptors, independent of psychological factors were necessary. The lack of consistent psychological scaling produced inconsistent data, that was influenced by factors such as those described by Slater (1986).

The location of the ideal position for the sensors was also an important outcome of the first phase. Various locations on the chest and back were tested, but during the trials it became apparent that moisture discomfort would start at the nape of the neck and slowly progress down the back and spread down and around the armpits toward the front of the body.

Overall, the first phase did not produce any reliable data but was crucial to the design of the journey trials because it provided an understanding for the nature of the experience and the type of data that was necessary to collect. The initial trial also indicated that the most prominent sensation that caused discomfort was the build-up of dampness which instigated the acquisition of a humidity recorder for the second series of trials.

2.2.1 Materials and methods

During the first stage, a Testo 175 Datalogger (Testo Ltd, Hampshire, UK) with two thermocouples was employed for the collection of objective data. One sensor took readings of the external environmental temperature and the other was taped to the skin on the subject's chest. The thermocouple was set to take readings every 15 seconds; a watch and a note pad were used to document the sensory experience. The data collected was compiled into a diary that included information on clothing worn, the weather conditions, the route and time of sensations.

A Rotronic Hygrolog D, Hygroclip SC05 (Rotronic Instruments (UK) Ltd, West Sussex) and mini disc recorder with microphone were acquired for the second set of trials. A psychological rating scale similar to the one used by Li (2005) was devised to represent the sensations during the data collection process. Objective data was collected using the Hygrolog and the Testo 175 thermocouple. The Hygroclip which recorded both temperature and relative humidity was placed at the nape of the neck and the one Testo thermocouple was recording skin temperature at the chest and the other recorded the external temperature. The devices were programmed to take readings every 15 seconds.

The trials took place using the same route and the same clothes during Dec 05 and Jan 06. Seven journeys were made in cold dry weather conditions. The subject maintained an average walking pace of 4k/h while talking into the mini-disc recorder, which was synchronized with the equipment. The route entailed walking at a mild pace from the subject's residence to a fixed point and back, which took approximately one hour.

The objective data was downloaded directly into a personal computer and the subjective data collected on the mini-disc was transcribed and coded using the sensation scales illustrated in table 1. Similar to those used by Li (2005) numerical values were associated to specific descriptors to facilitate statistical analysis. Discomfort sensations were attributed negative numbers because comfort is assumed to be neutral at 0 and any positive or pleasure sensations would be given positive values, however none were experienced.

Sensation Scales					
Comfort Level		Humidity		Thermal	
		Saturated	4	Boiling	4
		Very damp	3	Very hot	3
		Bit damp	2	Hot	2
		Evaporation	1	Warm	1
comfortable	0	Dry	0	Neutral	0
slight discomfort	-1			Cool	-1
uncomfortable	-2			Cold	-2
very uncomfortable/ sick	-3			Very cold	-3
				Freezing	-4

Table 1: Journey sensation scales

2.3 Findings

The raw data from both data-loggers and from the transcribed recordings were compiled into an Excel spreadsheet. The data was grouped by trial and the timeline was used to link both objective and subjective sets of data. The results for each trial were illustrated in two graphs, one demonstrating the readings from the humidity and temperature sensor that was located on the nape of the neck (fig 14) and the second graph combined information on the sensations experienced (fig 15). All the graphs from the trial are included in appendix 1.

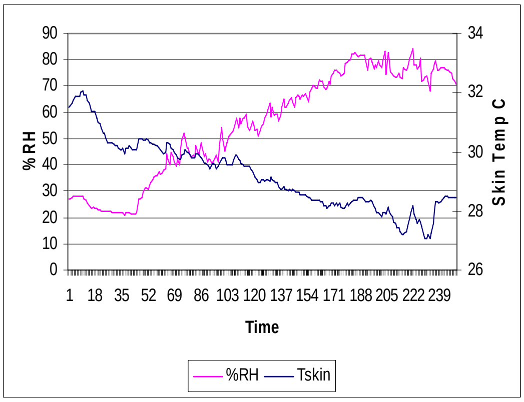


Figure 14: Objective trial data illustrating changes in skin temperature and microclimate relative humidity for the duration of the trial

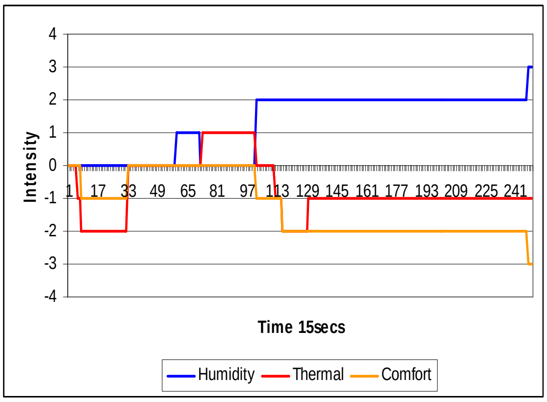


Figure 15: Subjective trial data illustrates the changes in sensation of moisture, heat and comfort for the duration of the trial

Figure 14 illustrates that during the trial, the subject's skin temperature dropped as the %RH in the microclimate increased. These results were not surprising as one of the functions of sweating is cool the individual. Figure 15 shows that the feeling of dampness is linked with the sensation of discomfort.

2.3.1 Comfort and temperature

The comparison of the trial data indicates that the perception of comfort is directly related to the perception of temperature, as the subject feels colder the comfort level decreases (fig 16). These findings agree with those of Li (2005) who also found that cold sensation is linked to decrease in temperature. Li (2005) also demonstrated that a drop in skin temperature is directly linked with decrease in sensation of warmth. The range of skin temperature that contributes to the sensation is relatively narrow, Gagge et al (1973) found that differences in skin temperature that cause discomfort range between 1-3^{o}C (Gagge and Gonzales, 1973) , this also agrees with the findings of the Journey trials.

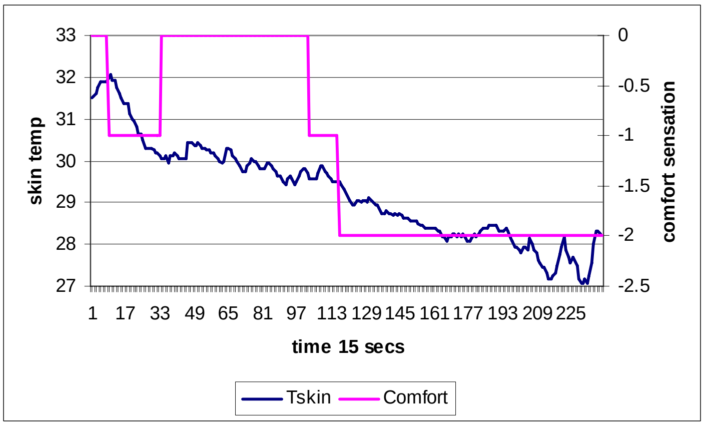


Figure 16: Corresponding objective skin temperature data with subjective comfort sensations for the duration of the trial. Discomfort at the beginning of the trial (10-30 mins) was experience as a result of stepping from a warm to a cold environment. This is reflected in the steep drop in skin temperature. Once activity levels had been maintained for a period of time the subject resumed an indifferent sensation, the subsequent drop in skin temperature is caused by perspiration.

2.3.2 Comfort and relative humidity

The findings also demonstrate that high humidity in the microclimate is directly linked to sensations of discomfort. Figure 18 shows that during this particular journey sensation of discomfort was initiated at 60%RH.

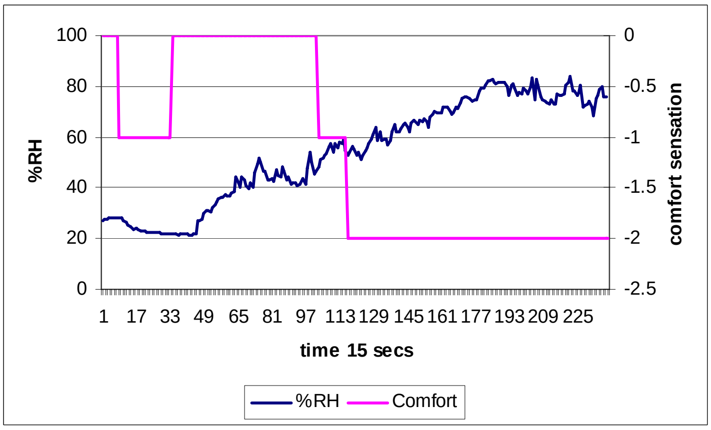


Fig 18 Corresponding objective relative humidity data with comfort sensation for the duration of trial. A steady increase in relative humidity is coupled with a steady decrease in comfort sensation.

The link between decrease in comfort sensation and increase in humidity identified in this work agrees with findings of previous research (Scheurell et al., 1995, Li, 2005, Hong et al., 1988). Also, the results show the skin temperature decreasing as the relative humidity in the microclimate increases, this also agrees with previous research (Ha et al., 1999, Li, 2005).

2.3.3 Comfort Zone

The data from the sensors and the transcriptions were combined to identify what conditions in terms of temperature and relative humidity characterize a comfortable microclimate (comfort zone). The subjective data enabled the separation of the raw numerical data into conditions of comfort and discomfort. The numerical data also came in pairs (skin temp. & %RH). All the pairs of numerical data that occurred during a period of comfort were combined into a graph to identify the rate of recurrence of particular combinations of %RH and temperature. The results are illustrated in figure 19.

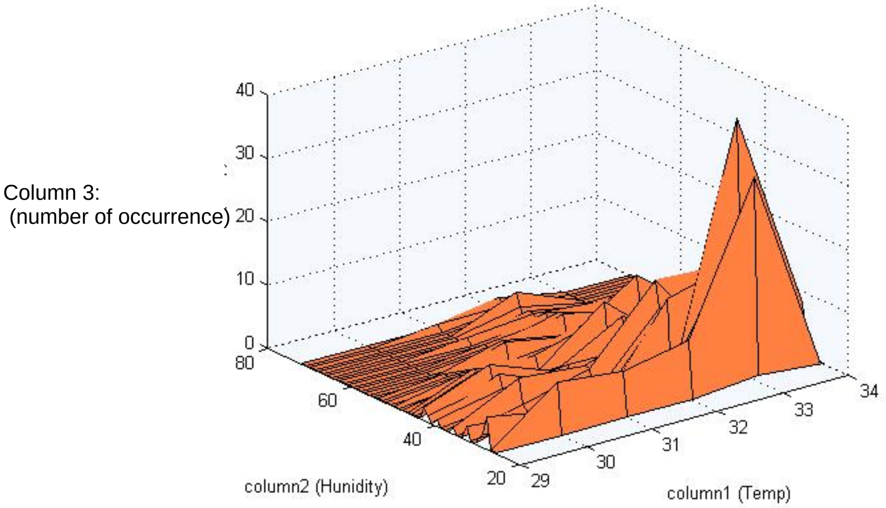


Figure 18: Data correlation; number of occurrence (column 3) of specific skin temperature (column 1) and %RH readings (column 2) during periods of perceived comfort.

Column 1 represents the temperature on the skin at the point where the % RH (humidity) measurements are recorded in column 2, and column 3 represents the rate of occurrence in which a particular RH and T_{skin} occur. The graph illustrates that the particular subject felt comfortable when the microclimate relative humidity was between 30- 65% and the skin temperature between 29-34°C.

Is it possible to identify skin temperature and relative humidity boundaries of comfort-discomfort? There are many points of both this work and the findings of Li (2005) that agree. It is also possible to extract a ‘comfort zone’ based on Li’s (2005) data. However the average external conditions of the Journey trials were 7.5°C and 95% RH; those of Li (2005) were 20°C and 80% RH. However as n=1 in the journey trials, it is not possible to identify if and how external conditions effect the parameters of physiological comfort (table 2); further investigation is necessary in order to establish this.

	Average External Temp.	Average External RH	Preferred Skin Temperature	Preferred %RH
Journey	7.5 °C	95%	33°C	<50%
Li (2005)	20°C	80%	34.4°C	<55%

Table 2: Physiological comfort limits

2.4 Discussion

The physiological discomfort relevant to this project is caused by rapid decrease in skin temperature coupled with sharp increase in microclimate humidity. Current ‘smart’ textile technologies employ temperature variations to trigger property changes (see section 1.2.3). Li’s (2005) findings confirm the negative effects of decrease in microclimate temperature near the surface of the skin on the sensation of comfort in a controlled environment. These are echoed in the results of experimental out-door work.

Decrease in skin temperature though is not necessarily exclusive to discomfort sensations. According to Cabanac (see section 1.3.1), the affect or ‘pleasantness’ of a thermal stimuli is determined by one’s internal state (Cabanac, 1971), therefore if an individual is hot, cold stimulus will be perceived as pleasant and vice versa.

It is well known that skin temperature also drops as a direct result of perspiration to cool the individual during periods of strenuous activity. It is apparent that evaluation of thermal stimuli is not exclusively bound to the nature of the stimulus but other indirect parameters, which are not represented in the microclimate of the clothing system and is therefore not an ideal trigger.

Phase Change Microcapsules (PCMs) produced by Outlast use a preset temperature to trigger retention or release of energy from the environment (microclimate or external). This technology has found many market applications from socks to garments designed for use in extreme conditions; however it poses several limitations in the delivery of physiological comfort. Although PCM textile systems are defined as smart materials, they do not respond exclusively to the user’s needs as the functionality is executed independent of the wearer’s physiological condition. There is every possibility that the amount of heat stored/ emitted is not enough to ensure the wearer’s comfort, or deliver the required amount at the proper time. Also, the performance (amount of energy stored and released) is directly related to the quantity of microcapsules used in the fibre of coating. Often high volumes of PCM are required to obtain an effect noticeable by the wearer, however the presence of large amounts of microcapsules have been found to compromise the quality and conventional properties of a textile (Tang and Stylios, 2006).

Shape Memory Polymer (SMP) membranes use temperature to manage the moisture resistance of a composite textile system. The success of these products is based on the assumption that below a preset temperature, the individual will require insulation and above this temperature the individual will produce excess moisture. DiAplex and C-change membranes are mainly applied to textile systems in external garments, so that the textile responds to the conditions of the external environment. This would be ideal for urban conditions where the environmental temperatures can change rapidly from hot to cold, but similar to the PCM mechanism, the textile is unable to take into account the activity of the wearer which potentially could compromise the effectiveness of the product and risk increasing physiological discomfort instead of protecting it.

Temperature is a poor trigger for adaptive textile systems designed to enhance the sensation of physiological comfort and products using such mechanisms are promising but flawed. This doesn’t mean that moisture is the optimal option simply by process of elimination. Results from both the journey trials and the work of Li (2005) clearly link the sense of discomfort with increase in microclimate moisture; this also agrees with the findings of Ha (1999), Berger (2000). However, slower rates of increase of humidity don’t have such a dramatic impact on comfort (Hong, Hollies et al. 1988) and could remain undetected for longer periods.

Also, given that moisture sensation is closely linked with an increase in water vapour pressure at the skin surface and a decrease in skin temperature (Hong et al., 1988), it can be argued that water vapour pressure and not relative humidity is a more representative factor to isolate as a trigger, but given that the temperature variations within a clothing system are narrow, Gagge et al (1973) found that temperature can vary by 1-3^{o}C, the effect of temperature on vapour pressure is nominal. Therefore the moisture vapour content of the microclimate appears to be an ideal factor that would signify the onset of discomfort and successfully function as a trigger for an adaptive clothing system.

The generation of the Comfort Zone model is not to be taken too literally. The purpose is to identify a method of quantifying the data and create a set of requirements that would inform the specification of the adaptive textile system. The trials used a single subject, although there is some uniformity in the way humans respond to external stimuli (Greenwood, 1971). Further research is necessary to identify a range of factors that may influence one’s sensation; ethnic origin, age and gender as well as experience.

Conclusion

This chapter has reviewed the work of those who have studied the sensation of moisture and comfort in relation to the properties of textiles. Instruments are a preferred means for obtaining good quality data on properties such as the moisture vapour resistance of textiles. The results provide key indications of textile performance that can also be used to compare levels of comfort. These methods are inappropriate for application in this particular study because they focus solely on objective data whereas the aim here is to examine the link between stimulus and sensation.

Psychophysical scaling is a proven method for linking subjective and objective data to produce concise and useful results. This chapter has discussed the work of some of those who have applied these methods to the study of moisture sensation and comfort in relation to textile properties. However, these studies have focused on local areas of skin as opposed to the microclimate of a clothing system.

Li (2005) found that psychophysical methods are applicable to the study of the effects of microclimate on comfort and perception of dampness in a controlled environment. The design of the Journey trials employs similar methods conducted in an urban environment instead of a laboratory. The findings between the two studies agree which indicates that the methods used could also be applicable to non-lab based studies. However, this is not the objective of the study.

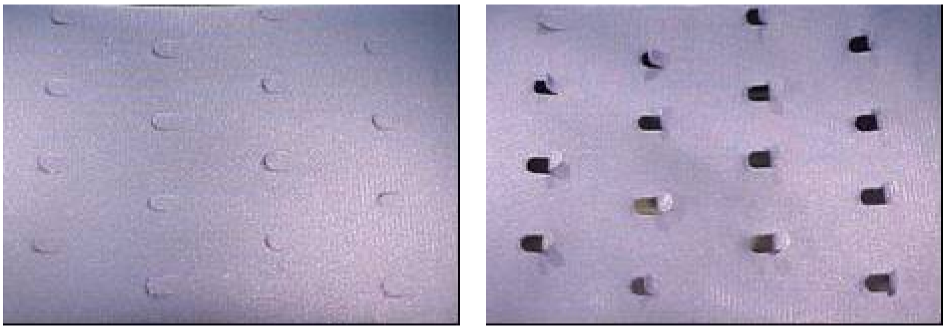
Current smart technologies and mechanisms used in textiles for clothing were reviewed in relation to the findings of the experimental trials. The outcome exposes potential limitations in the delivery of physiological comfort especially when the subject is active. It also becomes clear that microclimate or skin temperature is not an objective enough parameter to function successfully as a trigger for an adaptive clothing system, where as moisture concentration in the microclimate appears more promising.

The results suggest that moisture is the parameter this project should employ as a trigger in the design of an adaptive textile.

Chapter 3: Hygroscopic Shape Change in Botanical Structures

Introduction

The technology of current smart textiles and clothing products employs changes in temperature to activate their adaptive functionality. Existing products react to temperature from both microclimate and external environments; however neither is fully representative of an individual's needs as they do not take into account the wearer's activity. The moisture content of the microclimate however represents a more promising stimulus for adaptation as it is directly related to physiological discomfort and representative of the wearer's activity. This chapter will study examples of hygroscopic shape change in botanical structures and abstract core design principals, to inspire a mechanism that could be applied to textiles. This will be followed by the description of a series of sorption[29] analysis experiments conducted on some botanical samples reviewed in the literature and compared with properties of cellulose textile fibres in order to identify similarities and possible platforms for technology transfer.



a. composite textile in dry conditions b. in damp conditions

Figure 19: 'Pinecone effect' on composite textile (source: Dawson (1997))

Previous research conducted by Dawson identified the opening and closing actions of the pinecone bract as a potential paradigm for technology transfer (Dawson et al., 1997). The mechanism was developed into a composite textile

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[29] The simultaneous action of adsorption (water molecules adhering to the surface of the fibre) and absorption (water molecules penetrating the amorphous regions of the fibre)

system comprising a woven, polyester, light weight textile and a nonporous hydrophobic/ hydrophilic membrane such as those marketed under the Sympatex brand (fig 19). Although Dawson's (1997) work confirmed that it was possible to transfer the mechanism from the biological context into a textile structure, this particular design has limited application in clothing (discussed further in chapter 4).

3.1 Hygroscopic mechanisms in plants

Hygroscopic contraction and swelling is a mechanism used to power numerous functions in nature. This study focuses on structures that enable seed and spore dispersal because the actuation mechanism utilises dead cells that require no additional energy to operate and the behaviour is recurring. This specification ensures the identification and study of simple mechanisms that would facilitate technology transfer into textile structures.

Conifers are serinotinous plants; they can retain seeds in canopies for many years. Pine cones store seeds until favourable conditions signal their release (Lamont et al., 1991, Pijl, 1972). Ther are a variety of cues, fire (pyriscience) is the seed release trigger for many types of pine in Australia and South Africa. Other conifers, usually found in Northern Europe wait for dry conditions (xeriscience) for seed dispersal. The pine cones studied by Dawson are a xeriscience example.

Atmospheric moisture is a common cue for seed dispersal in the plant world; xeriscience is common among many plant species in non-desert conditions. While in the dessert where rainfall is sparse, some plants wait for damp conditions to disperse their seeds such as the fruit of *Mesembryanthemum* (Garside and Lockyer 1930) and Plantago (Fahn and Zohary 1941). Preliminary work identified two key systems used to operate such mechanisms: cohesion and imbibition (absorption of moisure)

3.1.1 Cohesion

Mechanisms based on cohesion use the forces created between water molecules and cell wall to load a spring in the plant, which usually facilitates the release of spores. The motion is enabled by specialized cell wall structures made from combinations of reinforced areas impermeable to moisture and fine permeable regions (Ingold, 1939). Ingold (1939) identified the cohesion mechanism in the sporangia[30] of the Filicales [31] and the elaters[32] in Cefalozia (Liverwort) (fig 21). Both structures are composed of cells that exhibit local reinforcement, illustrated by darker areas in figure 20. These are initially filled with water; in dry conditions the moisture is lost through the permeable part of the cell wall, as a result the increasing cohesion forces created between the water and the cell wall eventually cause the water molecules to separate thus creating a gas phase.

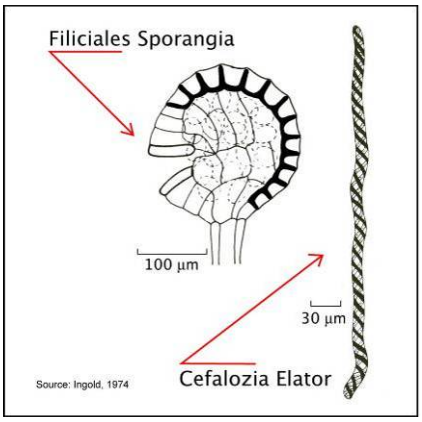

Figure 20: Cohesion mechanism in sporangia and elater

The sporangia (fig. 21) are described as a biconvex lens approximately 1/5 mm in diameter; the active cells in this case are found along the rim of the lens shape and comprise the annulus, which extends from the stalk to approximately 2/3 of the sporangium rim. The inner and radial walls are much thicker than the

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[30] A single-celled or many-celled structure in which spores are produced, as in fungi, algae, mosses, and ferns. Also called spore case.
[31] The largest order of modern ferns.
[32] A tiny elongated structure that forces the dispersal of spores by the absorption of moisture. It is either a band attached to the spore, as in horsetails, or a filament occurring among the spores, as in liverworts

outer walls (Bower 1926; Ingold 1965). Their role is twofold, one is to produce spores and the other is to disperse them (Ingold, 1939, Goebel, 1905) in favourable conditions (Bower, 1926).

Each of the sporangium cells is filled with an aqueous solution at maturity; dry conditions cause the water to evaporate through the thin area of the cell wall. This causes the volume inside the cell to decrease, in doing so; the thicker walls are drawn toward each other distorting the cell (Ingold 1939) as it is unable to replace the lost moisture (Papihar 1965). The behaviour is similar to a loading spring (Goebel 1905), which is released suddenly during transition into gas phase.

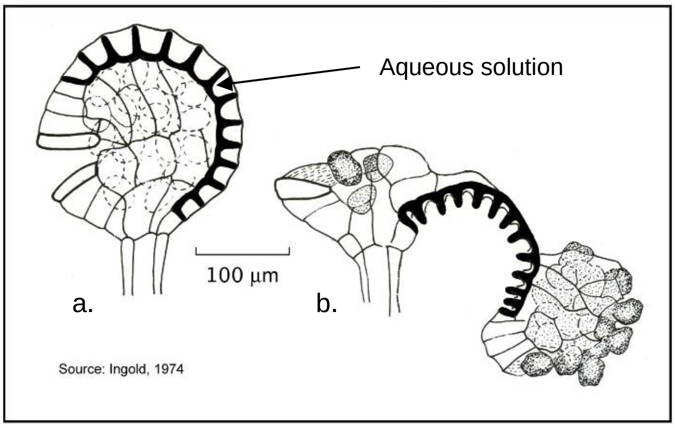

Figure 21: Bending motion of the sporangia annulus. a. cells are filled with aqueous solution. b. Dry conditions cause the moisture to evaporate through the thin layer of the cells. Source: (Ingold, 1974)

The elater of the Cephalozia (fig 20) is a long tube-like structure covered with spores whose cellulose wall is internally lined with two reinforcing helical bands that are filled with an aqueous solution. In dry conditions the moisture evaporates from the interior of the structure through the permeable areas of the elater wall causing the volume to decrease. These areas of the wall bend inwards causing the spirals to twist as the thick bands are drawn tighter and tighter towards each other. The cohesion forces between the water and the cell wall resist the twisting motion until a point is reached which induces the gas phase and the elaters suddenly untwist assuming their original shape (Ingold 1974).

3.1.2 Imbibition

Imbibition is based on the principle of shrinking and swelling of plant fibres as they lose or imbibe water respectively from the amorphous regions of the cellulose fibres (Harlow et al., 1964). The mechanism is actuated in the dead cell walls of a particular structure where opposing forces are created either between two cell types or within the wall of the same cell (Fahn and Werker, 1972). These forces are caused by differences in swelling between the cells or cell parts, which in turn are managed by the orientation of their cellulose microfibrils (Fahn and Werker, 1972, Oudtshoorn and K. Van Rooyen, 1999). Imbibition is responsible for the dehiscence (splitting or bursting open) of fruits and flowers but more relevant to this project, it manages the dispersal of seeds and spores by controlling the deployment of specific plant organs or their parts (Fahn, 1947, Pijl, 1972).

3.2 Literature review on sample range

An elaborate array of actions involved in seed / spore dispersal are powered by imbibition, from opening and closing of a structure (e.g. pinecone bracts) to leaping, creeping and digging (awns, hairs etc). Although, there is great variation in the manifestation of the mechanisms, the principle is based on two simple types of movement: bending and twisting. This section will review an indicative range of samples based on the type of movement they demonstrate to compare mechanisms and identify similarities.

3.2.1 Bending

Hygroscopic bending is the most predominant movement demonstrated among the botanical samples studied. The opening and closing mechanism of the pinecone uses this motion. Harlow (1964) found that two types of mature sclerenchyma[33] cells found within the pinecone bract were responsible for the opening and closing mechanism (figure 22). One type of fibre is tightly packed in clusters of long, fine strands (fig 23a) that resemble cables (Dawson, 1999) that extend from the axis of the cone and along the length of the bract. The other type are short rectangular structures with thick cell walls (fig 23b) known as sclerids (Harlow et al., 1964).

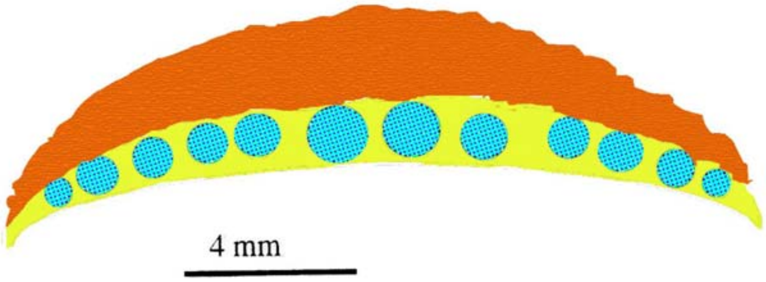

Figure 22. Cross section of pine cone bract, blue = fibres, yellow = sclerids

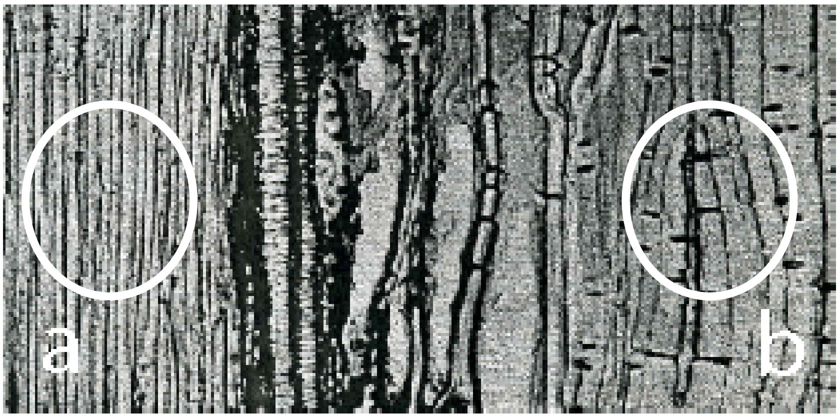

Figure 23: 50X magnification of pine cone bract cross section showing two types of sclerenchyma cell (Source: Harlow ,1964). a. Fibres (long thin sclerenchyma cells). b. Sclerids (Short fat sclerenchyma cells)

Although the two forms of tissue demonstrate identical sorption properties (Dawson, 1999) the dimensional swelling varies greatly. During imbibition, the fibres demonstrate a negligible change in length, whereas the sclerids are

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[33] Dead cells with heavily thickened walls containing lignin. Two main types: fibres and sclereids.

capable of significant swelling. Dawson (1997) found that by comparing the changes in length of the two tissue types, the sclerids had a coefficient of hygroscopic expansion approximately three times greater than that of the schlerenchyma fibres (Dawson et al., 1997).

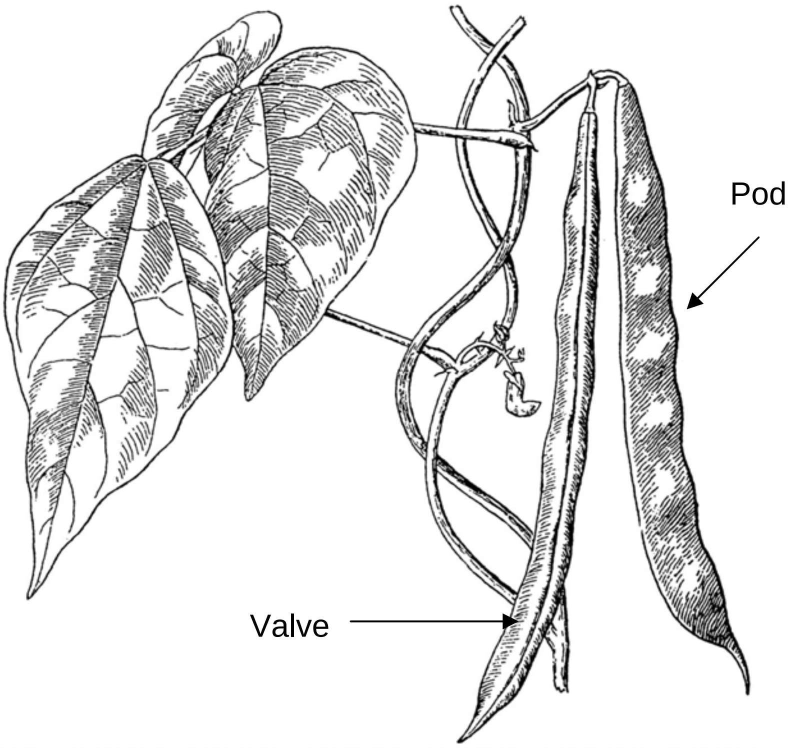

Figure 24: Illustration of legume pod before splitting. Pod pericarp is made of two valves. (source:http://www.nap.edu/books/030904264X/xhtml/media/p2000325eg172001.jpg)

Polarized light microscopy was used to identify the orientation of the cellulose in the two types of tissue (Dawson et al., 1997, Harlow et al., 1964). The schlerenchyma cells were found to have microfibrils orientated at approximately 30° to the cell axis and the sclerids were found to be 74°- 90° [34]. This difference in microfibril orientation is believed to be the controlling factor in the amount of dimensional swelling demonstrated by a particular fibre. Allan and Wardrop (1964) compared X-ray diffraction studies on the cellulose microfibrils in dry and wet pinecones and found that the lattice spacing of the crystalline regions were the same in both wet and dry samples. However as the microfibrils of the

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[34] Dawson et al (1997) found the angle to be 74° and Harlow et al (1964) 90°, Dawson suggests that this discrepancy in orientation may have been caused by treatment applied to the cellulose in order to isolate it from other materials such as lignin for study.

amorphous regions were wider apart in wet samples, it was therefore assumed that the shrinking and swelling of the cell walls is due to the desorption and sorption (both adsorption and absorption) of moisture respectively from the microfibrils and the non-cellulose matrix separating them (Wardrop and Allen, 1964).

The pericarp of legume pods (fig.24) is made of two valves that enclose the seeds. At maturity, environmental triggers (dry conditions) cause many types of pod to split open separating the two valves. The valves can either bend or twist to release the seeds inside. The mechanism activating the valve separation (referred to as *dehiscence* in botanical literature) is similar to that responsible for the opening and closing of the pine cone.

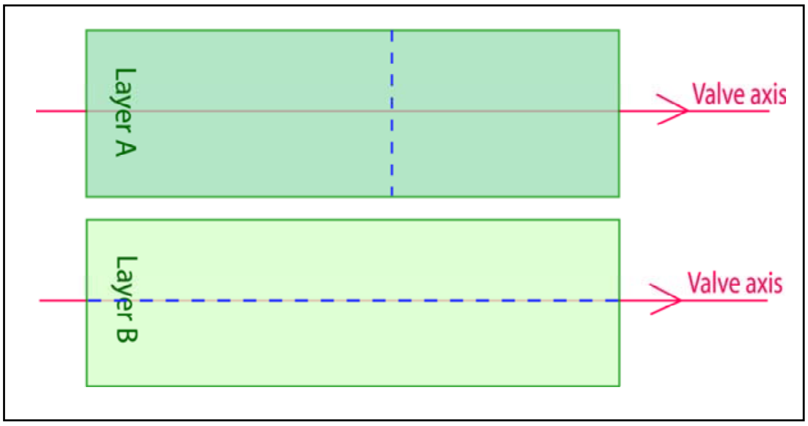

Figure 25: Microfibril orientation of bending legume valve. (Blue dotted lines indicate microfibril orientation.)

Unlike the pine cone, where two types of schlerenchyma tissue can be easily distinguished by eye, the mechanism in the legume valves is comprised of two layers of cells whose walls consist of differently orientated cellulose microfibrils or a single cell whose wall structure varies (Fahn and Zohary, 1955). For purposes of simplicity, two layers will be used to visualize the mechanism (fig 25).

Bending valves were found to have microfibrils orientated at right angles to each other (Fahn and Zohary, 1955) creating areas of cells with difference coefficients of hygroscopic expansion. In dry conditions layer A (fig 25) contracts in length more that layer B. the resulting changes in curvature between the two layers cause the valve to bend and the pod to dehisce.

The four segments comprising the geranium seed capsule (fig 26) curl in dry conditions and straighten in the presence of moisture. This mechanism was explored by Fahn et al (1972) who found that the cross section of the capsule was made of heavy strands of fibres divided into two layers (fig 27). The cellulose of the outer layer (layer A, dark green) was orientated across the width of the structure at a 90° angle to the axis of the pod, whereas the microfibrils of the inner layer (layer B, pale green) were orientated diagonally to the tail axis. Upon drying, the fibres in layer A contract longitudinally more than the fibres in layer B (Fahn and Werker, 1972). The uneven dimensional changes between the two layers, as in the bending legume pod valve, cause the pod segments to bend open to release the seed.

Figure 26: Geranium seed capsule in dry conditions, four pod segments bend upwards to release seeds

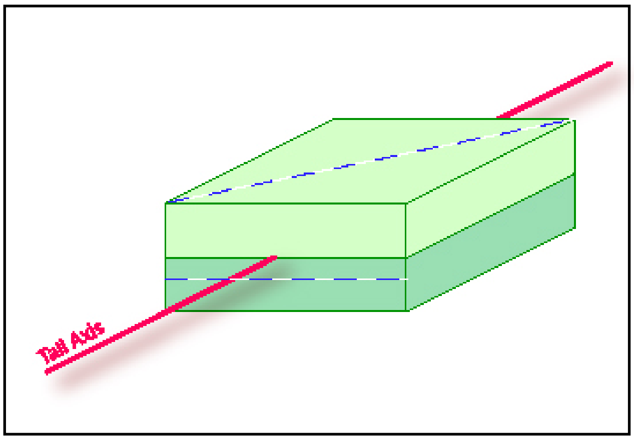

Figure 27 Microfibril orientation of geranium seed capsule (Blue dotted lines indicate microfibril orientation)

The principles of imbibition can be concentrated in a particular part of the cell to induce localized motion. This is often demonstrated in seed hairs, bracts and calyces[35] (Pijl, 1972, Fahn and Werker, 1972, Upholf and Hummel, 1962). Such a variation enables the seeds and their dispersal mechanisms to perform an elaborate array of movements such as to creep, leap or dig into the ground.

Anemone seeds rely on wind for dissemination; in dry conditions the hairs attached to the seed expand in area by curling outward from the base of the hair (fig 28) this function is similar to a sail or parachute as it captures the wind thus enabling the seed to be carried by a long distance.

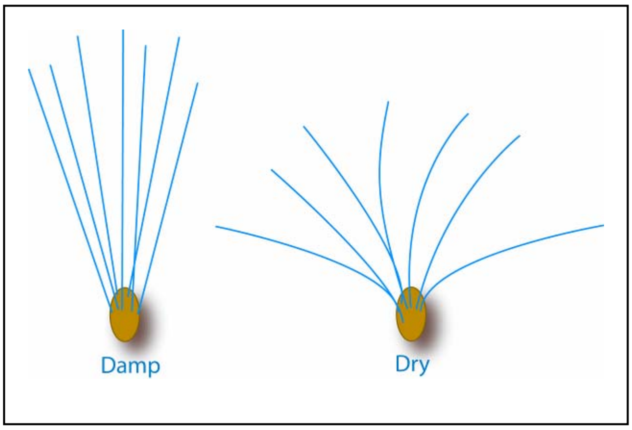

Figure 28 Bending motion of Anemone seed hairs

The action is caused by a local variation in the structure of the cell wall at the base of the hair (fig 29), adjacent to the seed. The one side of the cell wall is fine and the cellulose microfibrils are orientated along the hair axis; the facing wall is thicker and the microfibrils orientated at orthogonal to the hair axis, the latter contracts more in the direction of the hair axis (Upholf and Hummel, 1962). Similar structural variations have been identified in wheat awns[36] (Elbaum et al., 2007), where the mechanism is used to actuate a drilling movement that enables the seed to burrow into the earth.

Similar to the Anemone, Tamarisk seed hairs increase the area they occupy by bending at the base of the hair to use the wind for dissemination (Fahn and

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[35] Calyx= the group of sepals, usually green, around the outside of a flower that encloses and protects the flower bud

[36] a stiff bristle projecting from the tip of a plant organ such as the sheath surrounding a cereal or grass seed

Werker, 1972). The Tamarisk demonstrates a peculiar structure illustrated in figure 30. The cells forming the actuation mechanism are highlighted in blue, in dry conditions the active region contracts and the hair curls in the direction of the active cells. This mechanism has been described as a swelling hinge (Upholf and Hummel, 1962).

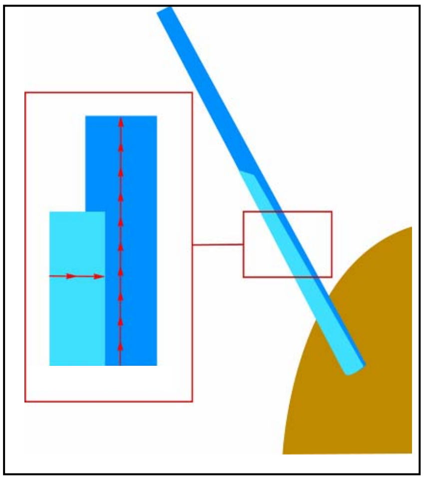

Figure 29: Base of Anemone seed hair. Light blue area represents the region that demonstrates greater dimensional hygroscopic shape change

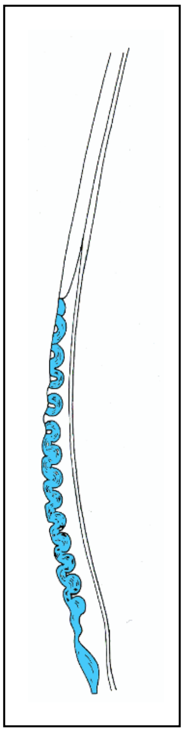

Figure 30: Cross section of Tamarisk seed hair. Area highlighted in blue: in dry conditions this area contracts causing the hair to bend

The spores of *Equisetum* also demonstrate hygroscopic shape change similar to the seed hairs. The projecting arms (fig. 31) are often referred to as ‘elaters’ because they are believed to aid wind dispersal. In dry conditions the expanded arms of the elators lock together creating clusters of spores that can be carried away by the wind (Ingold, 1939, Eames, 1936, Goebel, 1905, Ingold, 1965, Newcomb, 1888).

The first explanation of this mechanism was given by Newcomb (1888) who identified two layers in the protruding arms; one made from cellulose and the other composed of ‘tilted laminae separated by thinner plates of a substance with a different refractive power' (Newcomb, 1888). Ingold (1939) also identified the non-uniform nature of the active structure. In damp conditions the outer surface expands more than the inner. Ingold (1939) suggested this was because the layer whose dimensions altered significantly was able to absorb more water (Fig. 32).

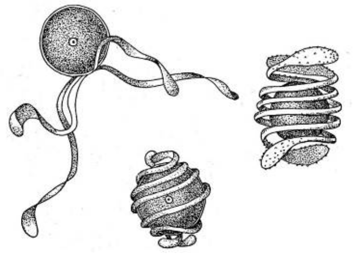

Figure 31: Arm movement of Equisetum spore. (source: (Papihar, 1965)

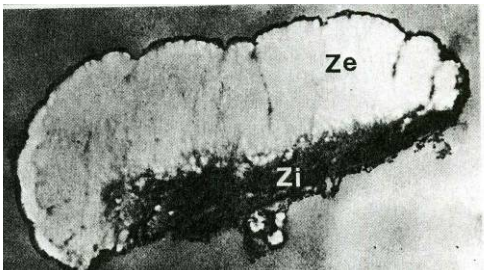

Figure 32: Cross section of spore arm (source: Tyron 1991)

Tyron et al (1991) used an electron microscope to explore the nature of the projecting arms. The findings confirmed the existence of two distinct zones consisting of an inner dense fibril layer overlain by a larger more homogeneous zone. The inner layer was found to be composed of cellulose, and the outer of non-cellulostic polysaccharides (Tryon and Bernard, 1991). The bending mechanism of *Equisetum* spore's protruding arms is different from those examined since bilayer system comprises of two adjacent layers made of different substances, whereas in the previous examples the two layers were made from cellulose.

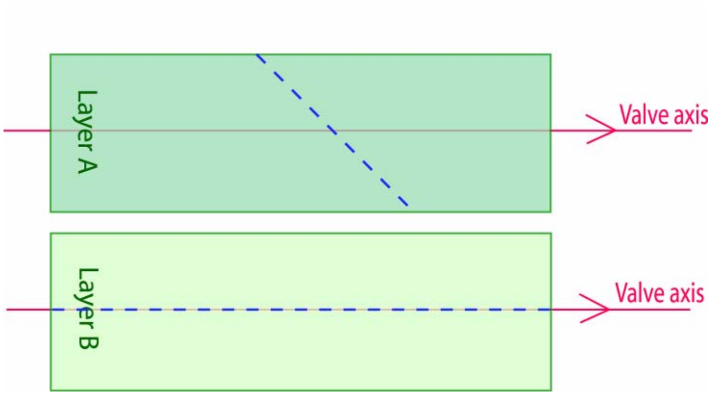

Figure 33: Legume valve microfibril orientation type 1

3.2.2 Twisting

In addition to the bending in some splitting legume valves, there are other species that twist. As the pod dehydrates, the valves wind into a cigar type structure. When re-hydrated; the structure regains its original shape. The hygroscopic mechanism that actuates the twisting motion is based on the same principle as bending but with some structural variations to the microfibril orientation between the two layers.

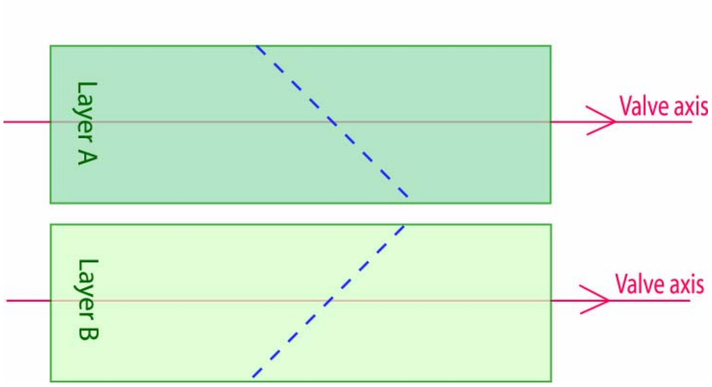

Figure 34: Legume valve microfibril orientation type 2

Fahn et al (1955) identified two variations that cause legume valves to twist. Type 1 (fig 33) demonstrates microfibrils orientated at 45^o to the axis of the valve in one layer and parallel to the valve axis in the other. In type 2 (fig 34), both layers may be orientated at 45^o to the axis of the valve but facing different direction or at right angles to each other (Fahn and Zohary, 1955).

3.2.3 Literature review summary

This literature review has demonstrated that there are variations to the imbibition mechanism that result in an array of movements. The process of abstraction used to simplify the mechanism into bilayer systems has revealed the basic tools used in nature to power hygroscopic mechanisms (fig 35).

3.3 Shrinking and swelling in cellulose materials

It is well known that materials, especially those used in clothing textiles tend to swell across their width as they absorb moisture and shrink during desorption. This behaviour is noticed among all hygroscopic fibres whilst most synthetic fibres remain unaffected by moisture. One exception is that of Nylon fibres which have been known to demonstrate nominal lengthwise swelling in high humidity (Wehner et al., 1987). Sorption can significantly affect the mechanical properties such as stiffness, strength and elasticity of fibres as well as alter the dimensions of a textile structure through shrinking and swelling.

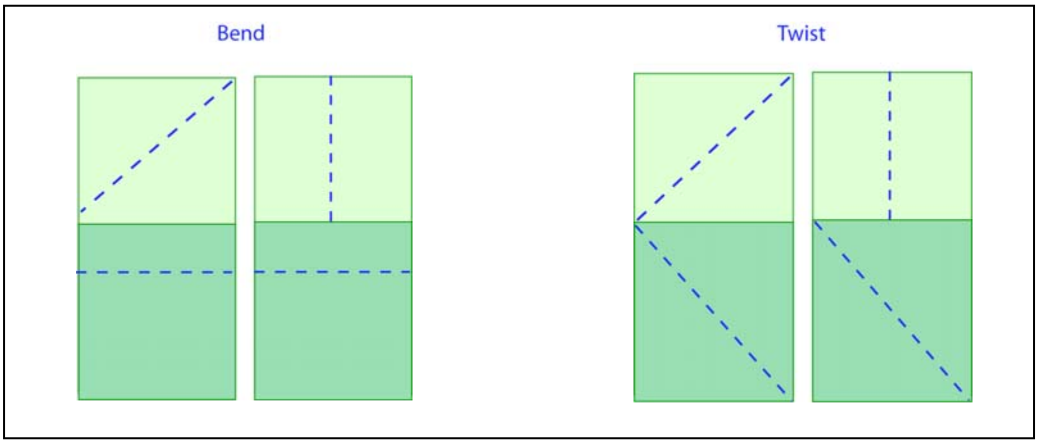

Figure 35: Variation of bilayer systems. (dotted lines represent orientation of cellulose microfibrils)

The volume of moisture that can be retained by a textile fibre (referred to in the textile industry as *moisture regain*) is believed to be determined by the ratio of amorphous to crystalline regions within the cellulose microfibrils (Cook, 1984a). The level of crystallinity was found to be inversely related to moisture regain in cotton (Segal et al., 1951). The ratio in viscose (rayon) demonstrates greater areas of amorphous configuration hence viscose fibres demonstrate a 30% greater regain than cotton (Cook, 1984a).

Dimensional change in the two types of sclerenchyma responsible for the opening and closing mechanism in pinecones occurs in the amorphous regions of cellulose microfibrils and the non-cellulose matrix separating them (Dawson et al., 1997, Wardrop and Allen, 1964).

The molecules in the crystalline regions are held in place by hydrogen bonds, which prevent the fibre from dissolving. Water generally doesn't penetrate this region but adheres to the surface; therefore the majority of sorption occurs in the amorphous regions. During desorption, the link formed between fibre and water molecules are broken, as a result they can either attract more water molecules or attach to other fibres. The outcome depends on the amount of moisture in the environment. The likelihood of attachment requires proximity between fibres otherwise they are more prone to attract water molecules (Morton and Hearle 1975).

Sorption isotherms of biological materials are generally sigmoid. The difference in curves between the sorption and desorption is called hysteresis and reveals that not all the moisture absorbed by the textile is evaporated during desorption and that some is retained in the system. Following the study of sorption in cotton fibres Peirce (1929) proposed a two phase theory; he suggested that moisture first adheres to the surface of the cells, initially in monomolecular layer and then subsequent layers of water molecules build up on the surface. Increasing diffusion forces tend to cause transfer of moisture into the cell, these are opposed by the binding forces exerted by the surface molecules but eventually with increasing build up, the binding forces give in to the diffusion forces and some moisture penetrates the lumen of the cell and becomes trapped (Young and Nelson 1967).

Melyan (1972) noticed the dimensions of softwood samples were significantly greater after sorption than desorption. Hunt (1990) also noticed the hysteresis between shrinking and swelling during the study of softwood specimen of *Pinus sylvestris*. In the case of wood, dimensional shrinking and swelling is linked to the orientation of the cellulose microfibrils in the thickest layer (referred to as S_2 layer in the literature) of the fibre cell wall. Melyan (1972) studied 44 specimens of *Pinus radiata* in low humidity (0-30% RH) and found that the angle of microfibril orientation affected the amount of longitudinal swelling or shrinking. In particular, the greater the angle the more dramatic the dimensional shape change (Meylan, 1972).

The findings of Hunt (1990) also suggest that there are two types of bonding between water and cellulose; one dominates at lower humidity, is strongly associated with longitudinal dimensional swelling and exhibits little hysteresis. The other dominates in higher humidity, has no effect on dimensional changes but exhibits high hysteresis (Hunt, 1990). This conclusion echoes the two phase theory provided by Pierce (1929).

Both theories agree on the type of interaction between fibre and moisture. The wood theory supports the idea that water is responsible for dimensional swelling. In cotton at lower humidity the volume change is less than that of the absorbed water, which implies that the water molecules are packed into the fibre’s amorphous regions. With additional moisture the volume changes gradually become equal; indicating that the water is stored along the surface of the fibre. The volume changes become different again in regions of high humidity when the capillary spaces are filled with water (Morton and Hearle 1975).

The sorption properties of wood are superior to cotton fibres due to differences in the cellulose chemistry as well as other factors such as the presence of waxes in the cotton fibres which could reduce moisture adsorption (Pidgeon and Maass, 1930). However there have been no studies on other botanical examples such as those described in section 3.2. As it is not possible to isolate and compare different tissue types in the sample range because the different microfibril orientations are found within cell walls and not two separate tissue types like in the pinecone.

3.3.1 Experimental work

Materials & methods

The range of cellulose material for sorption analysis is illustrated in figure 37. The botanical samples included *Equisetum* telmateia (Great horsetail) spores, three types of legume and geranium seed valves. These were collected from the locations indicated in fig 37. The horsetail spores were allowed to dry at 24^{o}C and 50%RH and stored in an air-tight container, the other botanical samples were immersed in distilled water then the active tissue was isolated and extracted using a scalpel. The samples were left to dry in 24^{o}C and 50%RH. The Cisorp Water Sorption Analyser produced by CI Electronics Ltd (Salisbury, UK) was used to measure mass change gravimetrically.

Experimental Procedure:

The sorption analyzer was programmed to conduct a cycle of 17 steps: adsorption 10% to 90%RH and desorption 90% to 10%RH. The chamber temperature was set at 25^{o}C. The cycle's first step was at 10%RH. Relative humidity was increased by 10% till the RH value was 90% then decreased till the RH value was 10%. A sample was placed in each microbalance. Water sorption kinetic tests were carried out on each sample. The mass change of the sample was measured every 3 minutes and the equilibrium condition was set to <0.001% total mass change for a period ranging from 120 to 360 minutes and illustrated in kinetic graphs. The data was also used to produce water adsorption and desorption isotherms, the water uptake during equilibrium was plotted as a function of water vapour pressure or relative humidity.

A list with all the experiments conducted along with notes on observations can be found in appendix 2

Sorption Analysis Sample List		
Description	**Origin**	**Supplier**
Equisetum telmateia	Box, Wiltshire	VK
Medium Legume	BA2	JFVV
Small Legume	BA2	JFVV
Large Legume	Botanical Gardens, Kandy, Sri Lanka	VK
Geranium	BA2	JFVV
Californian Cotton	California, USA	Cotton Inc
Mid-South Cotton	USA	Cotton Inc
Easter Cotton	USA	Cotton Inc
Viscose 1,7 dtex	Austria	Lenzing AG

Table 3: Sample list

3.3.2 Results

The absorption and loss of moisture of four geranium seed samples were measured using the moisture sorption analyser. The kinetic diagram showing the profile of time of full sorption desorption cycle for two samples is illustrated in figure 36. The fibres reached equilibrium stage at each moisture interval. The total percent of mass absorbed was plotted against the relative humidity to illustrate the equilibrium moisture sorption/desorption isotherm for each individual sample. The isotherm data was compiled into a single graph shown in figure 37. The same procedure was followed for each sample type; figure 37-41 illustrates the isotherm data from the botanical samples. Figure 42 illustrates the data from raw cotton fibres from 3 US regions and figure 43 data from viscose fibre tests.

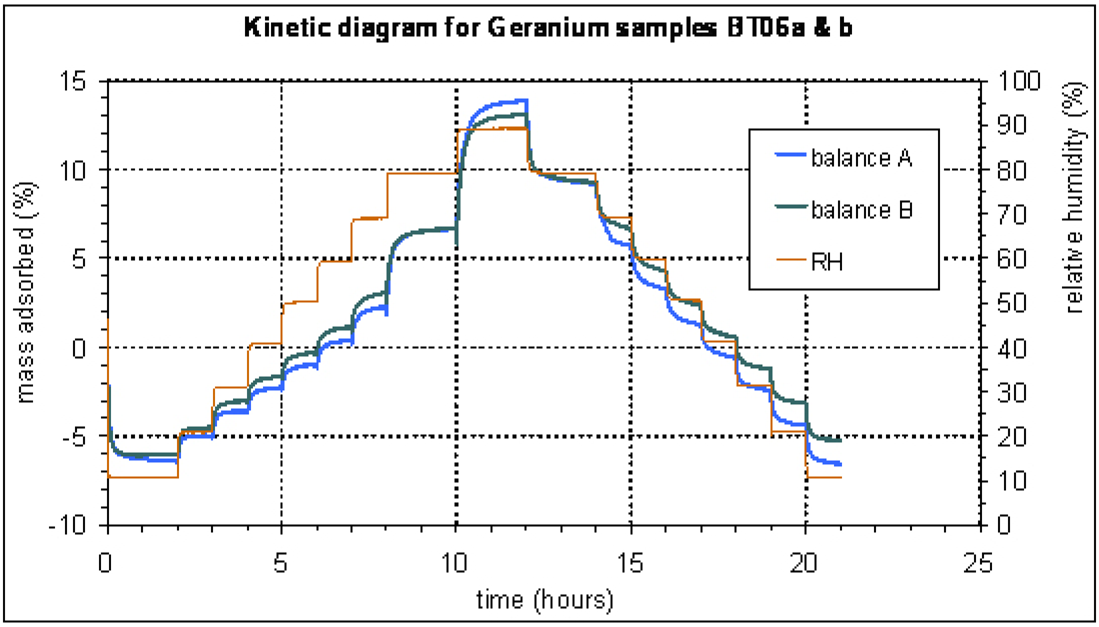

Figure 36: Geranium seed pod kinetic graph

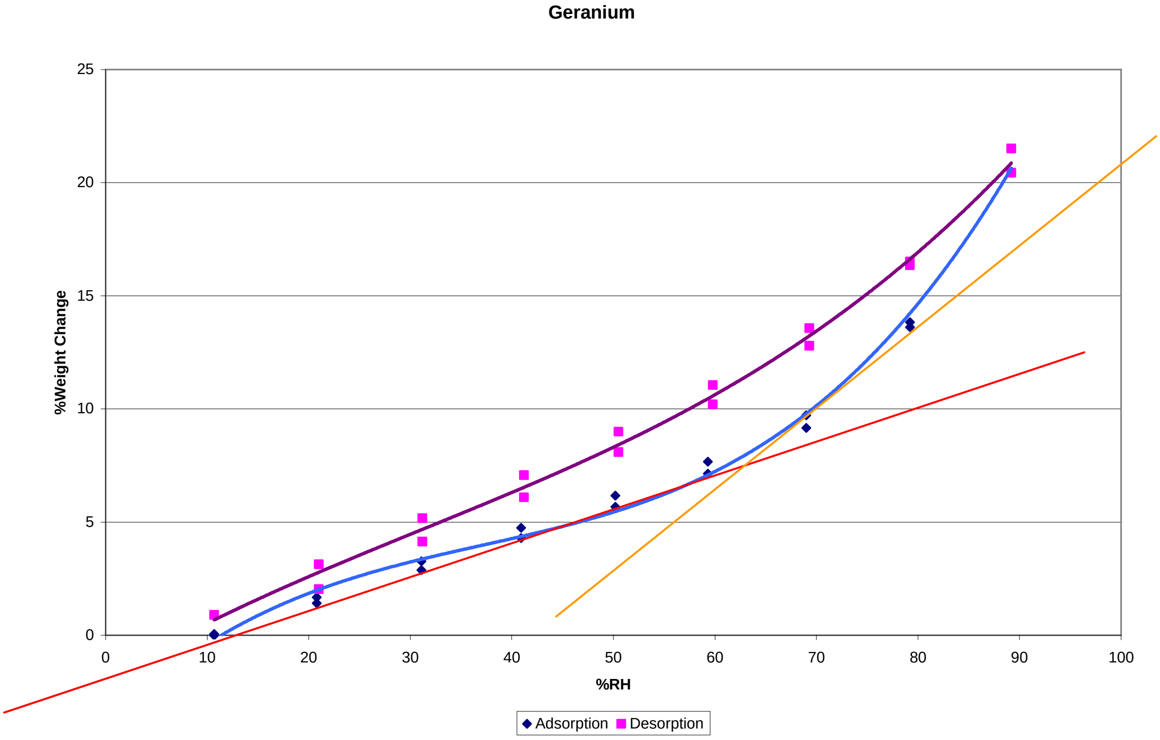

Figure 37: Geranium seed pod isotherm graph from two samples. From 10-50% RH the moisture uptake is gradual, indicated by the red line which illustrates the angle of the curve, from 50 -90% RH, the angle (orange line) increases sharply indicating a larger uptake of moisture. The desorption isotherm follows a more steady loss of moisture.

During absorption (fig. 37), the geranium pod sample absorbs moisture gradually until about 50% RH, the angle of the absorption isotherm takes a sharp turn upwards. This suggests that moisture absorbed by the fibres stops around 50%RH, as humidity increases beyond this point, water molecules adhere to the surface of the fibres. According to Hunt (1990), moisture induced shape change in this particular geranium pod stops at 50% RH. Although during desorption the adsorbed moisture is the first to be lost, the fact that hysteresis occurs at higher humidity suggests that moisture may still be penetrating the fibres and shape change taking place, or water has penetrated the fibre lumen.

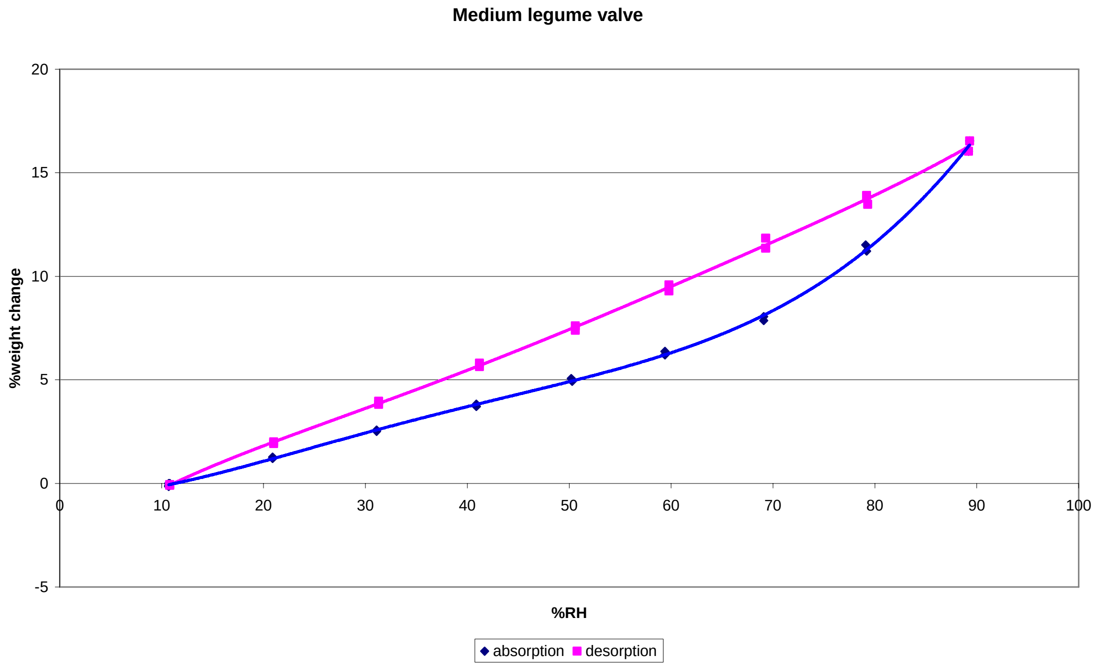

Figure 38: Medium legume isotherm graph Geranium. From 10-65% RH the moisture uptake is gradual, from 70 -90% RH there is a sharp increase in moisture uptake. The desorption isotherm follows more steady loss of moisture

The medium legume valve (fig. 38) absorbs moisture steadily till 65% RH at which point a steeper angel indicates a higher rate of moisture uptake. Similar to the geranium, it appears that shape change stops at 70% at which point water molecules are adhering to the surface of the fibres, hysteresis at higher humidity either indicates shape change is still occurring or moisture has penetrated the cell lumen.

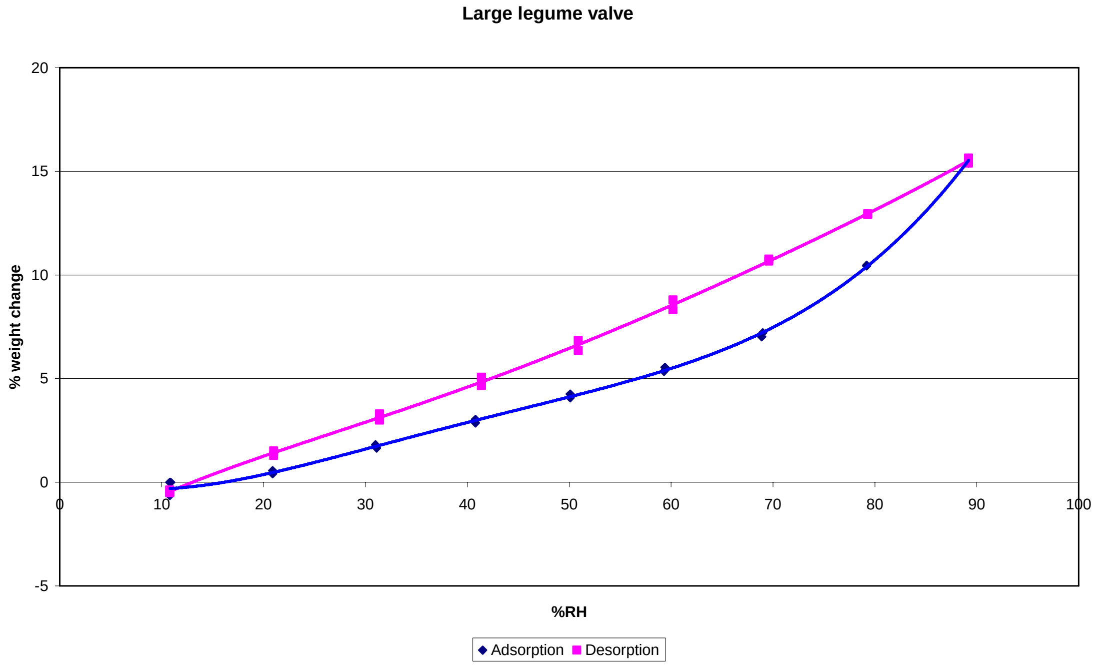

Figure 39: Large legume isotherm graph. From 10-65% RH the moisture uptake is gradual, from 65 -90% RH there is a sharp increase in moisture uptake. The desorption isotherm follows more steady loss of moisture

The large legume valve (fig 39) absorbs moisture steadily till 65% RH at which point a steeper angel indicates a higher rate of moisture uptake, echoing the properties of the medium legume. Again, it appears that shape change stops at 65% at which point water molecules adhere to the surface of the fibres, hysteresis at higher humidity either indicates shape change is still occurring or moisture has penetrated the cell lumen.

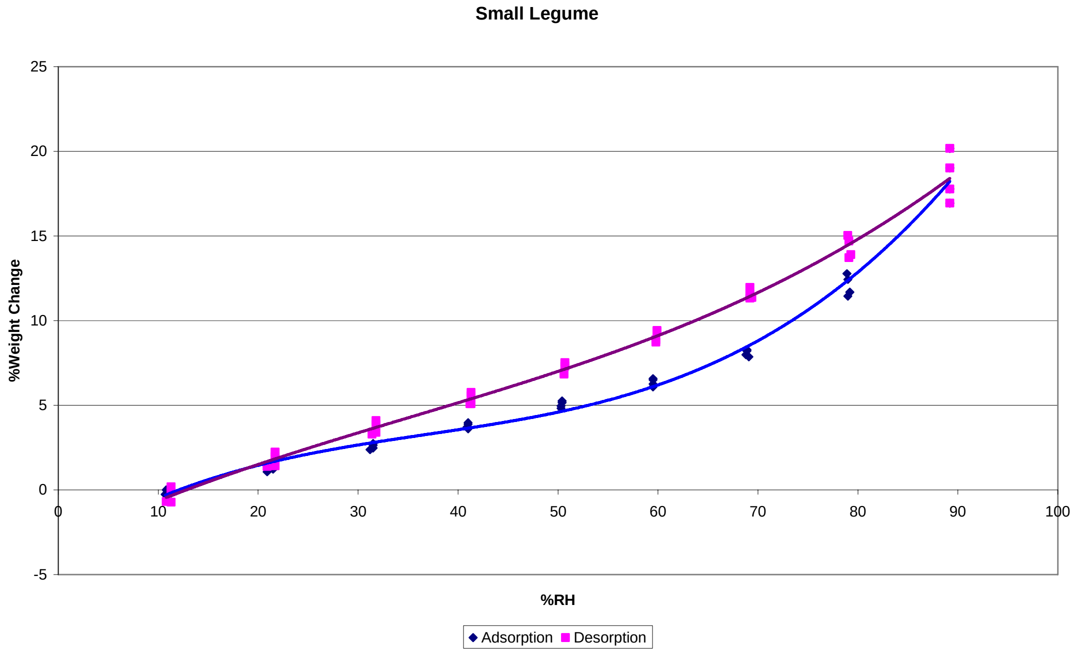

Figure 40: Small legume isotherm graph From 10-60% RH the moisture uptake is gradual, from 60 -90% RH there is a sharp increase in moisture uptake. The desorption isotherm follows more steady loss of moisture.

The small legume valve (fig 40) absorbs moisture steadily till 65% RH at which point a steeper angel indicates a higher rate of moisture uptake, echoing the properties of both the medium and large legume. Again, it appears that shape change stops at 60% at which point water molecules adhere to the surface of the fibres, hysteresis at higher humidity either indicates shape change is still occurring or moisture has penetrated the cell lumen.

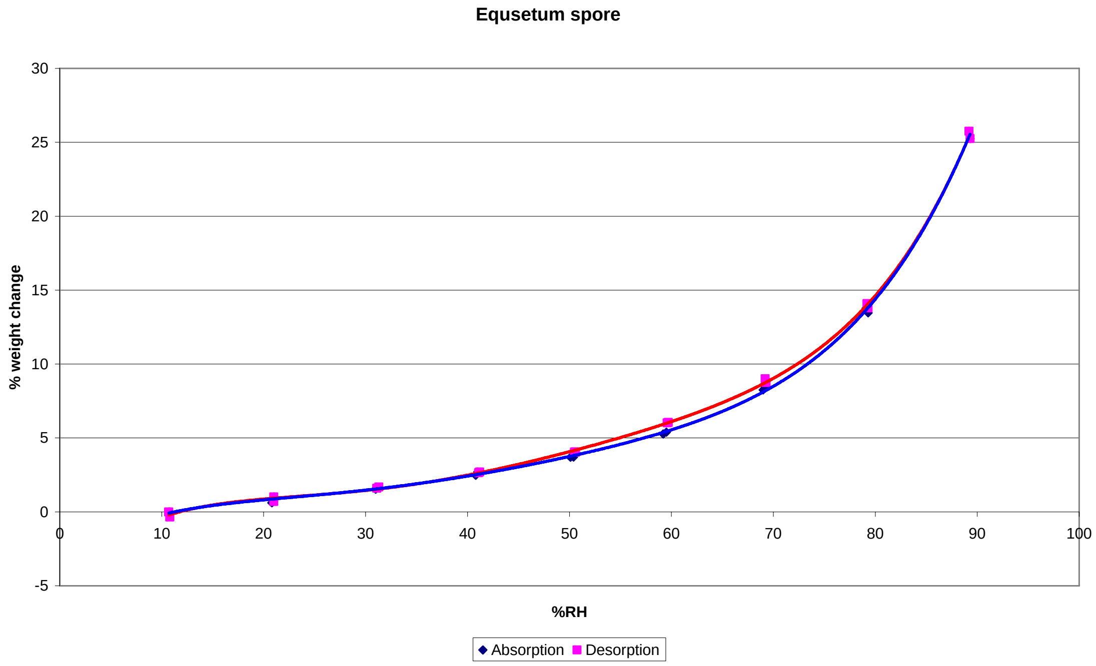

Figure 41: Equisetum spore isotherm graph. From 10-60% RH the moisture uptake is gradual, from 60 -90% RH there is a sharp increase in moisture uptake. The desorption isotherm is virtually identical to sorption.

The *Equisetum* spores (fig 41) absorb moisture steadily till 65% RH at which point a steeper angel indicates a higher rate of moisture uptake, it appears that shape change ceases at 65% RH. Given that there is virtually no hysteresis in the system, all moisture absorbed and adsorbed is lost. This is a very unusual result; it may be due to the structure of the spore elaters which is different from the other samples. Here shape change is not instigated by two types of sclerenchyma cells but a bilayer system made of cellulose and non-cellulostic polysaccharides which rules out any possibility of moisture absorption by cell lumen.

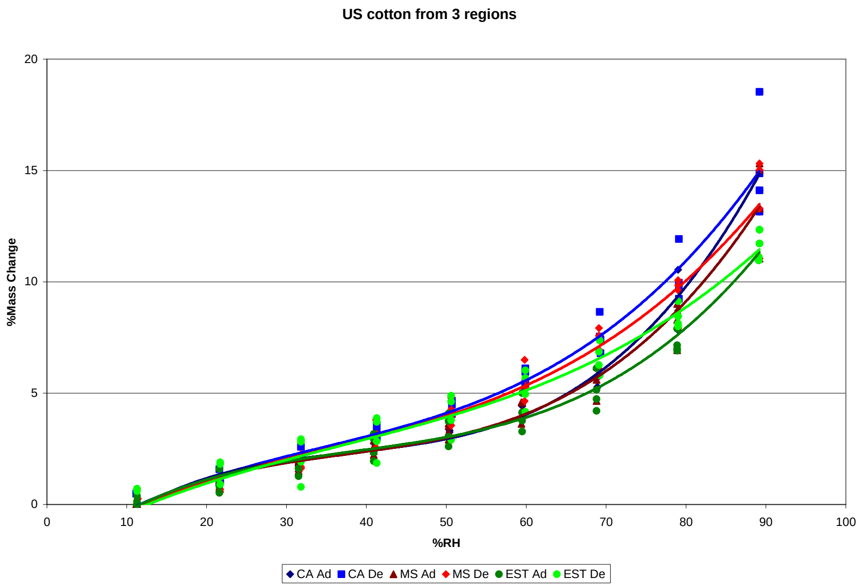

Figure 42: Isotherm graph of 3 types of cotton fibre. Green = Easter Cotton, Blue = Californian Cotton, Red = Mid-South Cotton. From 10-60% RH the moisture uptake is gradual, from 60 - 90% RH there is a sharp increase in moisture uptake. Californian cotton fibres are the most absorbent, followed by Mid-South and Easter cotton fibres.

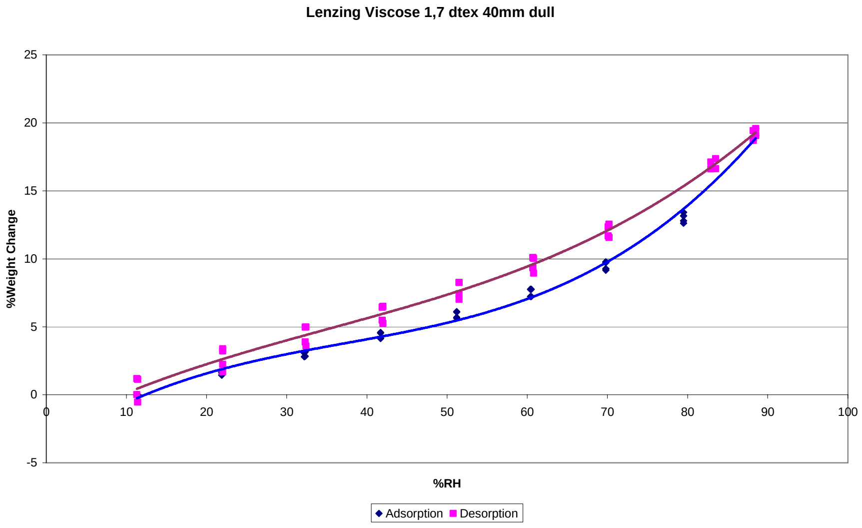

Figure 43: Viscose fibre isotherm graph. From 10-55% RH the moisture uptake is gradual, from 60 -90% RH there is a sharp increase in moisture sorption. During desorption, some moisture is retained in the fibre even at lower humidities. This suggests that moisture is trapped in a single layer of molecules lining the microfibrils in the fibre’s amorphous regions.

	90%	80%		70%		60%		50%		40%		30%		20%		10%	
Description		**ad**	**de**	**ad**	**de**	**ad**	**de**	**ad**	**de**	**ad**	**de**	**ad**	**de**	**ad**	**de**	**ad**	**de**
Easter Cotton	11.72	7.5	8.5	5.5	6.9	4	5.1	3	4	2.5	3	2	2	1	1	0	0
Mid-South Cotton	13.29	8.9	9.9	6.1	7.5	4.1	5.5	3	4	2.5	3	2	2	1	1	0	0
Large Legume	14.98	12.9	10.8	7	10.5	5	8.5	3.5	6.5	2.5	4.5	1.5	2.9	0.8	1	0	0
Californian Cotton	15	9.5	10.5	6.2	8	4.1	5.8	3	4	2.5	3	2	2	1	1	0	0
Mid Legume	16.04	11.5	13.5	8.5	11.5	6	9.3	4.8	7.2	3.8	5.8	2.5	3.5	1.5	2	0	0
Small Legume	19.01	12.5	14.5	8.9	11.9	6.2	9.2	4.9	7	3.9	5.1	2.9	3.5	1.5	1.5	0	0
Viscose 1.7dtex[37]	19.58	13.5	15.8	9.9	12.2	7.5	9.5	5.9	7.5	4	5.7	2.7	4	1.3	2.2	0	0.5
Equisetum	25.74	16.8	17	9	9.9	4.1	5.1	2.5	3	1.8	2	2	2	1	1	-1	-1
Geranium	26	17	19	11	14	7	11	5	8	4	6.5	3	4.5	2	2.5	0	0

Table 4: Approximate moisture uptake (mg). The Geranium seed pod demonstrated the most % weight change during sorption, while the Easter cotton fibre were the least absorbent in the range.

3.4 Discussion

This study compares the sorption properties of botanical samples with those of cotton (natural fibre) and viscose (regenerated man-made fibre) used commercially by the textile industry. Although all the samples are primarily composed of cellulose, there is great variation in the amount of moisture uptake between the samples. In general terms, the biological samples absorbed more moisture than the commercial fibres. The sorption properties of cotton fibres were compared to those of wood by Pidgeon (1930) who found that the difference in moisture uptake was due to differences to the cellulose chemistry (α-type cellulose is less hydrophilic but present in cotton while more β– and γ–type is more hydrophilic and present in wood), other factors could be presence of waxes on the fibre primary wall which is broken down during processing for use in textiles (Cook, 1984b).

Fibre molecules can be present as both crystalline and amorphous forms. In the crystalline regions the molecules are aligned close together, these regions

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[37] Used in textile industry to measure linear density of fibres and yarns. Decitex (dtex) = mass in grams in 10 kilometre of filament.

are responsible for strength and stability and are virtually impenetrable by moisture. Areas of randomly arranged molecules (amorphous regions) account for stretch, flexibility and sorption properties of the fibre. Cotton is estimated to have 5-15% amorphous regions (Cook, 1984b). Viscose fibres have less crystalline regions (30% amorphous) than cotton which accounts for the higher uptake of moisture by viscose than cotton in the Cisorp trials. (Sheppard and Newsome, 1934, Okubayashi et al., 2004, Morton and Hearle, 1975).

The ratio between crystalline and amorphous regions in textile fibres is a key factor to the physical properties of textiles. Hygroscopic shape change in the botanical specimen (pinecones, legumes, seeds and spores) reviewed in the literature suggests that shape change is controlled by the direction of the cellulose microfibrils similar to the opening and closing behaviour in the pinecone mechanism identified by Harlow (1964). Fibrils aligned at 45-90^{o}angle to the axis of the pod, hair, bract etc create lengthwise swelling in the fibres or cell walls they constitute. However, microfibril orientation in textile fibres is predominantly along or close to [24.5^o in cotton (Onogi et al., 1996)] the fibre axis since this alignment attributes the necessary tensile strength that enables a particular fibre to be used for production of textiles. Also in the case of man-made fibres, the extrusion and stretching processes align the microfibrils parallel to the fibre axis; hence the transverse swelling noted in most textile fibres (Morton and Hearle, 1975).

The absorption and desorption isotherms often are different in the mid to high humidities, indicating that not all the moisture absorbed by the samples is lost during desorption. All samples tested demonstrate hysteresis between adsorption and desorption (Table 3), the least was noted in the *Equisetum* spores. This indicates that moisture is retained in each system, least of all in the *Equisetum* spores. Hysteresis was consistent in the cotton fibre range, when compared to the viscose fibres the area covered by the cotton was significantly less. This was expected as regenerated cellulose fibres are defined by more amorphous regions than natural cotton.

The commercial fibres studied were in loose form (separated from each other) whereas the botanical samples were obtained from a slice of tissue, which contain a cluster of cells. Morton (1975) suggests that in the case of textile fibres, dimensional swelling occurs at two stages, the first in the fibre itself at lower humidities, just like in the wood samples, the second occurs in higher humidities when capillary spaces (spaces between the individual fibres) begin to fill with water, this is important when fibres are packed together in yarns.

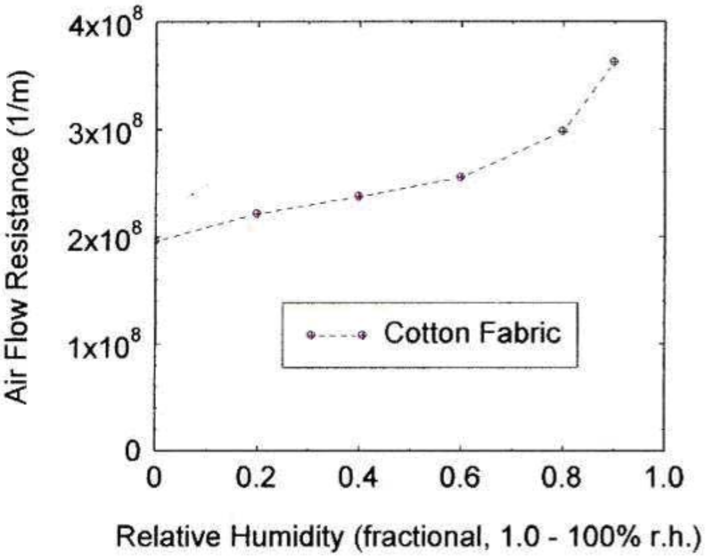

Figure 44: Effects of moisture on airflow resistance on cotton textile. As relative humidity increases, the cotton textile becomes less permeable, significant increase occurs at 60%RH. (source: Dr Gibson, U.S. Army Natick Soldier Research)

The range of United States cotton samples studied (fig. 42) shows no hysteresis at 10 to 25% RH. According to Hearl (1975), water is bound on a monomolecular layer onto the microfibrils in the fibres amorphous regions moisture adheres to the initial layer of water pushing the microfibrils further apart thus causing fibre swelling, from 60% RH upwards, moisture begins to build up in the capillary spaces between the fibres. This is also echoed in figure 44 that shows the effect of relative humidity on the air flow resistance of a woven cotton textile. Although the fibres used for the construction of the sample were not from the same source as those tested by the sorption analyser, there are similarities in performance. Air flow resistance (or air permeability) decreases at a slower rate until 60% RH, than at higher humidities. This suggests that the swelling caused by build-up in the capillary spaces has a greater impact on the permeability of this particular textile.

Viscose is a regenerated cellulose fibre that has about 30% more amorphous areas than cotton (Cook, 1984a) this means that there are more areas of cellulose microfibrils available for moisture to adhere to. This may account for the slower uptake of moisture during the sorption isotherm in figure 43. It appears that the layers of water molecules build up from 10-50%RH at which point the first type of swelling occurs. Capillary spaces are filled and the second phase of swelling occurs from about 70% RH.

Swelling in commercial fibres especially the hygroscopic variety which is closely related to comfort has a negative effect on air permeability of a textile. Inevitably, the very characteristic that renders these fibres comfortable in the short term, has a reverse effect in the long term. Observations on the performance of the range of samples studied suggests that an ideal textile structure would somehow absorb enough moisture to activate shape change, but prevent the type of swelling that occurs in higher humidity in textile fibres. This means that the adaptive mechanism needs to operate at low to mid humidity and prevent the increase in microclimate moisture into the higher regions. We would also be looking for a structure that demonstrates little to no hysteresis in order to avoid any unwanted moisture induced shape change.

Conclusion

Successful technology transfer from one discipline to another requires a vehicle that is common to both areas. Often the identification of the medium is disguised by domain specific language and cultural boundaries. In the context of this project, the link between the botanical structures investigated and innovation in textile technology is dimensional change caused by sorption of moisture. So far, this work has examined the effect of moisture interaction with examples of botanical tissue and isolated fibres used in textiles. The shrinking and swelling properties of the biological samples examined are used as an actuation mechanism, while the swelling of fibres is considered a problem in the textile industry as it reduced fabric permeability thus creating discomfort.

The hygroscopic and hydrophilic/phobic aspects of textile fibres and their relationship to comfort were discussed in chapter 1. These properties are favourable and directly associated with experience of comfort. Natural and regenerated fibres such as cotton, wool and viscose are hygroscopic. As a result they are breathable, provide insulation and help manage transitions from dry to damp environments (and *vice versa*). Synthetic fibres on the other hand, demonstrate poor hygroscopic properties and have been generally considered uncomfortable because they can generate static, cling and clammy sensations directly related to discomfort.

Sorption is the basis for the adaptive mechanisms that enable the management of spore and seed dissemination examined in this chapter. The hygroscopic shape change is induced by the swelling and shrinking structures resembling bi-layer strips where differences in hygroscopic expansion between the two adjacent layers cause the structure to bend or twist. The resulting motion depends on the degree and direction of which is controlled by the orientation of the cellulose microfibrils resulting in a wide array of actions (fig 35).

The sorption isotherms of both botanical tissue and textile fibres in conjunction with the theories of Hunt (1990), Morton (1975), Harlow (1964) and Peirce (1929) from the literature review, it was possible to begin to unravel the relationship between moisture sorption and shape change. The data from the cotton fibres echoed the results from a cotton textile tested for the effects of moisture on airflow resistance. Increase in airflow resistance is directly associated with swelling of the fibres in the yarn. The next chapter will review existing technology that utilises differential swelling in bicomponent systems to activate shape change in textiles and fibres.

Chapter 4: Hygroscopic shape memory technology in clothing

In their study of the pinecone, Dawson et al. (1997) compared the mechanism to that of a bimetallic strip that curls or bends when exposed to heat. The shape change is not permanent and the strip returns to its original shape when the stimulus disappears. Hygroscopic shape change in nature operates in a similar manor, in the sense that the deformation is not permanent and the plant part or organ reverts to its original shape when the moisture content returns to 'normal'. Materials that demonstrate these reversible shape changes that are triggered by a particular stimulus such as heat, moisture, electrical current etc are classified as 'shape memory', a relatively new field of material science.

'Shape memory' behavior has also been used in textile marketing literature to provide the illusion of added value to products. Key examples are the shape recovery properties of wool and elastane fibres. Wool owes its elastic recovery properties to the crimp in its structure and can elongate from 25% strain when dry to 50% when wet (Cook, 1984b). Elastane fibres (i.e. Lycra), due to their molecular structure, can extend to 800% of their original length and demonstrate 100% elastic recovery (Cook, 1984a).

This chapter will provide an overview of shape memory technology and its context in 'smart' materials. A brief review of existing applications in the clothing sector will be followed by a review of developments focused on hygroscopic shape memory behavior in textile fibres for clothing applications. A discussion of these innovations will reveal the limitations in the existing state of the art and opportunities for solutions.

4.1 'Smart' materials and structures

A new 'breed' of materials has emerged from various sectors such as aerospace and medicine from the late 20th century that demonstrate behavior described as 'smart' or 'intelligent'. The semantics of 'smart/ intelligent' materials and structures has caused great debate and there are several definitions spanning from the degree of ‘smart’ behavior of a particular material (Pratap et al., 2002, Zhang and Ming, 2001) to definitions extracted from industry surveys (Spillman et al., 1996). It is clear that as these new technologies emerge from one sector of material science and find applications in others, the vocabulary used to describe the properties may be relevant in one context but not another. The general consensus is that these materials or structures are able to sense and respond to changes in environmental conditions by altering their properties with greater or lesser degrees of complexity.

This project is concerned with structures that alter their shape in response to external stimuli similar to the botanical materials reviewed in the previous chapter. In the man-made world this behaviour is defined as shape memory and there are numerous such developments that have found application in sectors such as medicine, transport and even clothing. These structures can change from one form to another when exposed to stimuli such as light, temperature, electrical current, and pH which function as a trigger that actuates the shape change (Tang and Stylios, 2006).

Shape memory materials can be composed of mixtures of metals or polymers. Shape memory alloys (SMA) are able to deform at low temperatures and revert to their original shape upon heating. Most examples use temperature as a trigger for shape change but it is also possible to design materials that respond to changes within a magnetic field. SMA’s have many current applications as vascular stems, medical guide wires, orthodontic wires, vibration dampers, pipe couplings, actuators and electrical connectors, to name a few (Hu, 2007).

Shape memory polymers (SMP) can be designed to respond to a wider range of stimuli. These materials are made of linear block copolymers that have both hard and soft segments; the reversible phase transformation occurs in the soft segments and is responsible for the shape memory effect. SMP’s are much cheaper to produce than alloys. They can be biodegradable and therefore less harmful to the environment. Current applications are predominantly found in the medical sector. Attempts to apply this technology to the textile industry have proven problematic because the structural changes unique to the materials create behaviors that interfere with the basic requirements of textiles such as handle, drape and dimensional stability (Hu, 2007).

Shape memory materials can demonstrate changes in their mechanical properties, in addition to dimensional effects. Alloys for instance, can increase their ability to deform within a particular range of temperature and polymers can switch from soft to hard.

4.2 Shape Memory materials in textiles for clothing

In 2001 design company Copro Nove created a prototype shirt composed of Nylon and a SMA known as Nitinol. The garment (fig 45) wrinkled and deformed as a conventional shirt during wear, however, upon heating with an instrument such as a hairdryer the shirt would revert to its original shape[38] free of wrinkles. From a commercial perspective the prototype was not viable for mass production because of the high cost of the Nitinol. In 2001 a single shirt had an estimated market value of approximately £2,500.

However, shape memory polymers offer a much cheaper alternative as the raw materials are not costly and the manufacturing procedure involved is similar to those used for conventional man made textiles (Hu, 2007). One avenue that appears promising is crease and wrinkle recovery with several developments currently under way.

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[38] http://www.newscientist.com/article/dn1073-shirt-rolls-up-its-own-sleeves.html

Figure 45: Shape memory alloy shirt. (source: Copro Nove)

4.2.1 Shape memory polyurethane membrane (SMPU)

Membranes have been used in composite textile systems for wind and moisture management functions for decades with key brands such as Goretex and Sympatex. These products offer wind and water resistance to the outer layer clothing yet allow moisture vapor to escape from the interior of the system. In the 1990's Japanese based Mitsubishi Heavy Industries launched a novel membrane marketed under the trade name Diaplex [39]. This product boasts to increase and decrease its air resistance in response to temperature; in high temperatures, resistance would reduce and increase in colder conditions (fig. 46). The company claims that their product uses Brownian motion to achieve this functionality (above a certain temperature the vibrations create pores which allow the air that carries moisture and heat to escape) suggesting that the bonds between the membrane molecules 'relax' above a certain preset temperature. No data is available supporting these claims.

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[39] http://www.diaplex.com/intelligent.html, http://www.diaplex.com/techtour4.html

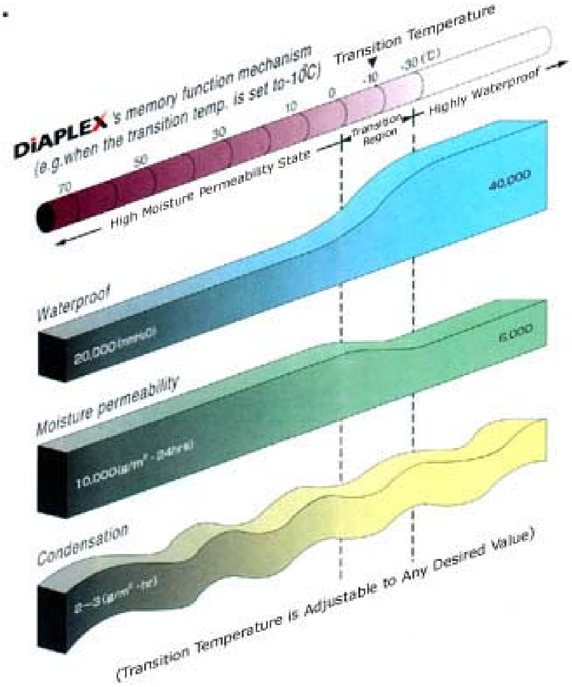


Figure 46: Diaplex performance chart (source: www.diaplex.com)
From top to bottom: a preset temperature of -10°C marks the transitional temperature. From 0 - -30 °C the membrane increases its water resistance and decreases its moisture permeability. It is not very clear what happens to the condensation.

Schoeller Textile AG launched a similar membrane branded C-Change in 2006 that uses Brownian motion to alter its permeability (fig 47). The marketing literature interestingly uses the pinecone to describe the mechanism. Although an effective visualization tool; the opening and closing mechanism of the pinecone bract does not react to temperature as discussed in the previous chapter, but to humidity.

The marketing literature in both products suggests that the temperature dependent Brownian motion increases and decreases the membrane's permeability to air and moisture; a unique property that enables the products to be classified as shape memory although there is no visible dimensional change. However, studies carried out at U.S. Army Natick Soldier RD&E Center, comparing these properties with other conventional membranes, failed to confirm this functionality and suggest that the performance claimed in the literature is in fact based on misinterpretation of results due to flaws in experimental method (Gibson, 2002a).

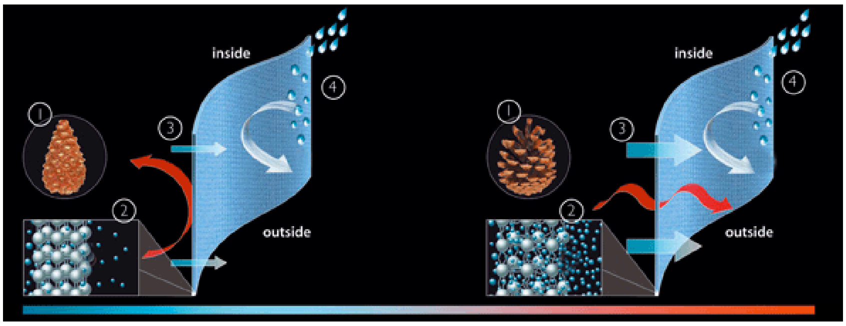


Figure 47: Functionality of C-change membrane (source: www.schoeller-textiles.com). Below a preset temperature, the membrane prevents the passage of air from the microclimate (left). Above this temperature the membrane structure allows the passage of air (right).

4.3 Hygroscopic ‘smart’ textile systems

Although it is questionable whether materials that swell and contract with moisture sorption can be considered to exhibit shape memory properties in the context of smart or adaptive materials, the swelling of cotton and viscose fibres does not make them smart materials. However, for the purposes of this study, a material will be included in this category if the swelling/ shrinking principle is used within a structure, as a functional part of a mechanism.

Sympatex developed a modification to their standard membrane products marketed under the trademark Phaseable. Motifs are printed onto the surface of their non-porous membrane product using highly swelling foam. The marketing literature suggests that as the foam absorbs moisture from the microclimate, it swells, reducing the volume of trapped air in the system. This method is believed to reduce the insulation properties of the garment and maintain low vapor pressure at the surface of the skin by the absorption of moisture by the foam. Nike exclusively licensed this product for a period of two years and therefore any data was protected by secrecy. This term recently ended but no data supporting this functionality has been made available.

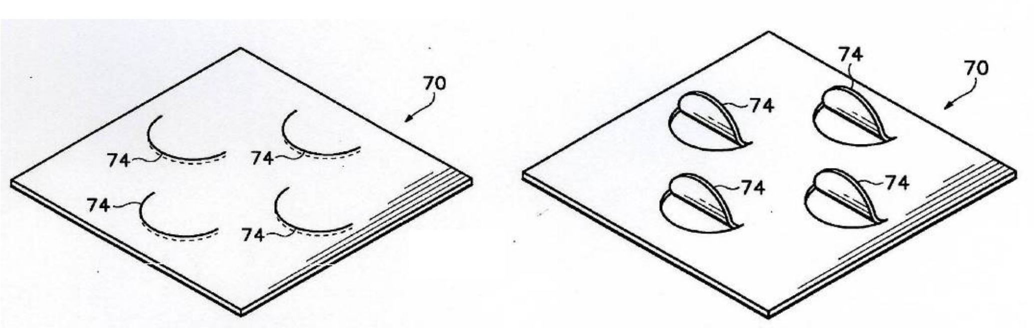
4.3.1 Pinecone effect

Dawson (1997) created an adaptive textile system based on the principles of the pinecone mechanism that increases its permeability to air in high concentrations of humidity. The composite textile was developed using a light weight synthetic woven structure laminated onto non-porous polyurethane membrane. Small u-shaped perforations were cut into the surface of the material illustrated in figure 21. An increase in relative humidity causes the polyurethane film to swell; as a consequence the loose sections of fabric created by the incisions curl back thus increasing the air permeability of the textile system.

Nike have developed a similar bilayer composite system that doesn’t use a textile/ membrane system but two layers of knitted or woven cloth with different swelling properties (US application no 2005208860), figure 48 shows Maria Sharapova wearing a tennis dress incorporating the active textile system during the 2006 U.S. Open Tennis Tournament.

Figure 48: Maria Sharapova in 2006 US Open (Source: times.com, 2006)

The composite textile applies a knitted or woven structure made from a hygroscopic yarn next to the skin, and uses a top layer made of a non-hygroscopic or non-swelling yarn; U-shaped perforations are created using either conventional slicing techniques or by laser cutting. As the wearer perspires the base layer swells while the top layer remains un-altered. As a result the loose sections of textile curl back similar to the structure developed in Reading by Dawson (1997). Figure 49 a. depicts the textile in a state unexposed to moisture and b. when the material has been exposed.



a. dry conditions b. exposed to moisture

Figure 49: Nike adaptive textile (source: U.S. application no 2005208860)

4.3.2 Moisture sensitive bicomponent fibres

Self-crimping bicomponent fibres have been used for many years to introduce stretch and bulk to both regenerated and synthetic fibres. The extrusion processes used to manufacture man-made fibres creates long straight filaments[40] that become fine yarns when twisted. These yarns give poor insulation as they trap nominal volumes of air. There are several methods that draw upon the thermoplastic properties of synthetic fibre polymers to introduce bulk and stretch into synthetic yarns such as air texturing, knit-de-knit, false twist etc; the method relevant to this study is the production of self-crimping fibres using bicomponent structures.

The most common bicomponent fibre cross-section is side-by-side (other types are sheath core and eccentric sheath core) that has many variations. Some basic ones are illustrated in fig 50. These fibres are composed of two types of polymer, one that contracts when exposed to particular conditions

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[40] A fibre of indefinite length.

(temperature, chemicals etc) and another part that doesn't. As a result, the different curvatures generated between the two layers once exposed to the particular conditions causes a permanent deformation in the structure resembling the crimp (waviness) common in wool fibres.

In 1982 Toray Industries published patent JP57056517[41] describing a fibre that had three different polymers in its cross section, one responded to moisture, the other to heat while one remained unaffected by either stimuli, thus creating a multi-component fibre able to alter its shape in different conditions. These fibres were designed for application in carpet textiles. Similar technology has recently been used to create self crimping fibres that alter the angle of the crimp in response to changes in moisture content for use in textile for apparel.

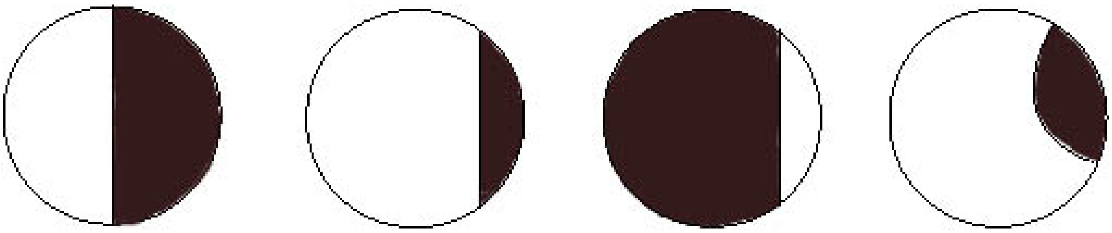

Figure 50: Side-by-side bicomponent fibre cross sections. White area resembles one polymer, black resembles another polymer

Two Japanese companies are currently at the forefront of this type of innovation; Mitsubishi Rayon Co and Teijin Fibres Limited. Both organizations have adapted the same method of producing self-crimping fibres but have used different chemistries to create filaments that alter their degree of crimp. Mitsubishi Rayon Co uses two types of cellulose acetate in a side-by–side bicomponent fibre configuration to create a filament that demonstrates a percentage of crimp[42] less than 10% at humidity above 95% and crimp above 20% at humidity 45% or lower[43].

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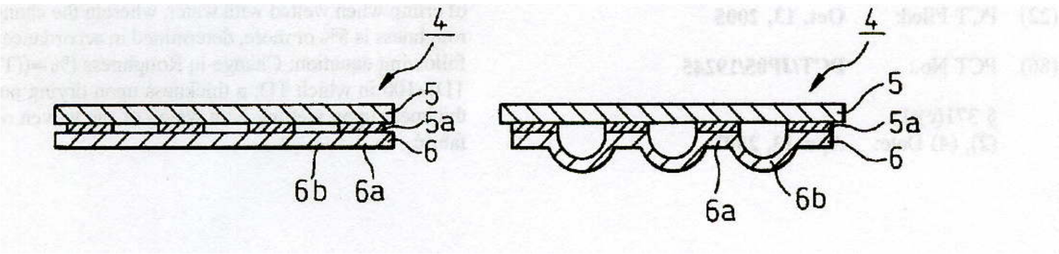
[41] Japanese patent no JP57056517
[42] The difference in length between the crimped and straight fibres, expressed as a percentage of the straight fibre.
[43] Worldwide patent WO2005/118931

The active filament was found to be problematic when used in a single layer textile structure, even as part of a blend. Owing to the reversible crimp behavior the structure created was dimensionally unstable and demonstrated slow drying time[44]. To resolve these problems a single layer of active textile is incorporated into a multilayered knitted or woven textile structure of non-active components whose weight can range from 100 to 350 g/m^2. This technology was originally designed for use in sportswear; therefore the ideal positioning of the active layer would be next to the skin.



a dry b wet

Figure 51: Textile concept containing moisture sensitive fibres (source: US2007/0270067 A1) In dry conditions the yarn containing the active fibre is contracted demonstrating maximum crimp of 20%, in damp conditions the active fibre relaxes, becomes less wavy and increases in length (10% crimp) thus creating a rough surface in areas where the active yarn is floating (not attached to the base fabric)

Teijin Ltd also used bicomponent technology to create a moisture sensitive fibre; instead of regenerated cellulose, two synthetic polymers were used[45] (modified polyethylene terephthalate and polyalkeylene glycol-containing nylon). This combination did present some technical issues, the adhesion, for instance, between the two polymers in the filament tended to split. The filaments also demonstrated poor durability during laundry and there was a significant reduction in crimp variation after processing. Teijin Ltd however, developed modifications to the fibre that improved these issues [46].

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[44] Japanese patent application 2002-180323
[45] Japanese patents JP2003239140
[46] Japanese patent JP2003239141

In 2006 Teijin Fibres Ltd published a patent describing the incorporation of its bicomponent fibre into a two-layer textile system (fig 51). As the active layer becomes wet, the moisture sensitive filaments increase their crimp and deform in the manor illustrated in figure 51b. Teijin Ltd describes this behavior as increasing the surface roughness of the textile. This is believed to enhance the wearer’s comfort by reducing the surface contact between the skin and textile, which is known to cause sticky sensations. The air permeability of the textile also increases to improve the evaporation of moisture. The textile system is designed for use in sportswear; the proposed application in the patent is the shape change side is next to the skin. This particular structural adaptation may reduce surface contact between garment and skin however, the pockets created resemble that of a pile structure (i.e. terry toweling) that increase the insulation properties which is an undesirable effect. The ideal would be to have a structure that reduces insulation in higher humidity.

4.4 Discussion

The textile systems developed at Reading University (fig 19) and by Nike (fig 48) clearly prove that the principles used to power seed dispersal in the botanical world can be applied to textile technology. Both design solutions involve a composite textile structure combining a hygroscopic and a hydrophobic textile component. The innovation is at the top end of textile structure hierarchy (fig 52). The introduction of new technologies into conventional clothing systems must take into account the basic functional requirements of clothing (fig 3) discussed in chapter 1, as a result the solutions presented by both Nike and Reading University present several limitations in the context of a clothing system.

In its current form, the technology can only be applied to external layers of clothing systems and/or single layer garments. This excludes a wide range of applications, and places the product in direct competition with existing systems such as breathable laminates (external layer garments) and high wicking performance textiles (single layer clothing). In both cases conventional textile products provide adequate breathability and comfort. Although the ‘added value’ is in the adaptive behavior, there are other compromises that inhibit the success of this innovation.

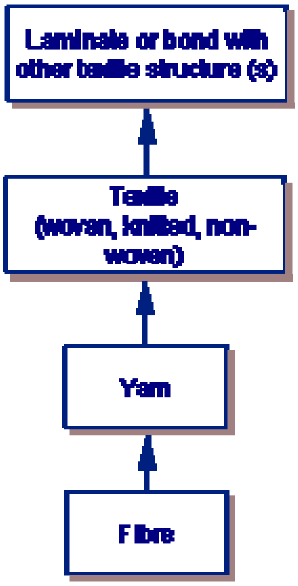

Figure 52: Conventional hierarchy of textile structure

One key limiting factor is that the adaptive behavior can easily be obstructed by accessories such as handbags, scarves, belts etc, therefore the wearer will be unable to personalize their ‘look’ or carry personal belongings other than in pockets incorporated into the clothing system. Also, the opening and closing mechanism is limited to areas of the back and chest. Application in the under-arm area is not suitable as the functionality will be inhibited by the movement and rubbing of the inner arm against the torso.

Another key factor is the aesthetic impact of the textile system: if the functionality is very visible, success of the product is linked to the quality of design and the skill of the designer in understanding and working with the technology. Applications in this category run a high risk of becoming a ‘gimmick’ just as in the case of the thermochromic pigment t-shirts and shorts marketed in Europe as Global Hypercolour (fig. 53) during the late 1980’s and early 1990's. The specialist pigments enabled the garments to be one colour when warm and another when cold.

Figure 53: Global Hypercolour t-shirt

Although the products were hugely successful initially, bad design in technology application (products were garment dyed therefore thermochromic pigments were embedded in the entire article) caused the colour change to emphasize hot, sweaty patches on the wearers back and arm pits. This highly undesirable side effect soon caused the rejection of thermochromic pigment for application in clothing, till recently designers such as Angel Chang, have reintroduced thermochromic pigments into their designs in print applications. Chang creates clothing that can alter its surface design with the use of a hairdryer (fig 54). However, invisible technology ensures wider consumer acceptance of new developments, and protects against 'gimmick' status that may inhibit further useful applications in a particular sector.

The principles of hygroscopic shape memory behavior have also been applied to the lowest level of the textile structure hierarchy (fig 52) using bicomponent fibre technology. These innovations have not been directly inspired by biological systems; instead they have evolved from a technique used to engineer crimp or bulk into man-made fibres. Section 4.3.3 reviewed the current state of the art in terms of moisture sensitive fibres that can manage the air permeability properties of a textile into which they are incorporated. The two versions of bicomponent fibre developed both demonstrate a reduction in crimp angle in dry conditions resulting in a flat yarn or indeed textile texture and an increase in angle when damp causing the textile system to develop a rougher surface.

Figure 54: Angel Chang heat sensitive print dress, Spring 2007. (source: angelchang.com)

Both proposed designs claim that the use of such fibres affects the air permeability of the textile system because the air pockets created in the high humidity phase when the crimp angle is minimum, encourage air renewal. The changes in surface texture, caused by the shape memory behavior also reduce the surface contact between textile and skin, preventing a sticky sensation closely associated with discomfort. There is no independent user trial data supporting these claims. The range of patents reviewed revealed that both regenerated and synthetic versions posed some technical issues such as splitting or reduced performance, however the issues important to this study have to do with the nature of the mechanism employed which is the same in both inventions.

Dimensional stability is a key limiting factor in these concepts; a fibre that alters its crimp angle will also alter its length, as the fibre contracts in length the textile will shrink in terms of length and width. Although the air pockets generated in the textile structure increase or become larger and the fabric may increase its air permeability (this is not clarified in the patents). The active side of the structure assumes a texture that resembles toweling or velvet structures which increase insulation as greater volumes of air are trapped in the system. This is highly undesirable; in fact the opposite functionality is required in conditions of high humidity.

Both developments disclose issues of dimensional stability and propose similar solutions; the incorporation of the active filaments into a supportive framework of multiple textile layers where the layer containing the moisture sensitive filaments is positioned next to the skin. Similar to Phaseable by Sympatex, the mechanism is designed to reduce the sticky sensation experienced by the wearer by minimizing skin/textile surface contact in damp conditions, however the fibres are limited to multilayer compositions and there is no data supporting the effectiveness of these structures.

Conclusion

The relatively new field of smart materials and structures has exploded in recent years, far-reaching novel applications promise a new era of materials able to sense and respond to environmental stimuli. This chapter focuses on materials that demonstrate structural/ dimensional changes in response to humidity variations and are suitable for application in the apparel sector.

Textile products currently available on the market claiming shape memory behavior are DiAplex by Mitsubishi Heavy Industries and C-change by Schoeller. If one is to accept the claims made in the marketing, these systems use temperature as a trigger. For reasons discussed in 2.4, these products are not suitable for the purposes of this study.

‘Pinecone effect’ was engineered into textile structure in the late 1990’s, originally developed for the Ministry of Defense; Nike commercialized the technology in 2005-06. This is a true milestone for Biomimetics, as it proves that the serinotinous seed dispersal mechanism employed by conifers can be realized in a textile system. However, in its current form, the design poses several limitations that prevent the technology from integration into textiles for apparel.

Two rival Japanese companies invented adaptive bicomponent fibres that alter their crimp angle in response to changes in environmental humidity around 2002. Both versions are based on the same principles but differ in their chemical composition; one is made from two types of regenerated cellulose the other from two types of synthetic polymer. Although initially both options provide promising methods in engineering an adaptive textile structure that can alter its permeability to air in response to changes in humidity, the fibres themselves and their proposed interpretation into textile structures are disappointing.

The review of existing developments clearly indicates that current inventions have targeted either end of the textile hierarchy (fig 52), the ‘pinecone effect’ is positioned at the very top, as the mechanism is based on the use of two textiles bonded together. The same way moisture sensitive fibres in contrast are positioned at the bottom of the spectrum. Both solutions present significant limitations in terms of application in casual apparel: perhaps the solution lies in the design of the yarn? The next chapter will explore this possibility.

Chapter 5: Concept design and development

Introduction

The findings of the work so far suggest that although the majority of smart textiles products use temperature as stimuli, the effects of microclimate moisture have been overlooked. Moisture sensitive shape memory fibres developed by two rival Japanese companies have been incorporated into smart textiles prototypes but have failed to produce a concept that can be integrated seamlessly into conventional clothing systems. Key limitations for both developments are the lack of dimensional stability in single layer textiles using the adaptive fibres.

5.1 Design requirements

The design of the adaptive system must fulfil the conventional requirements of textiles designed for application in apparel; fig 55 is an indicative map illustrating an overview of core functionality.

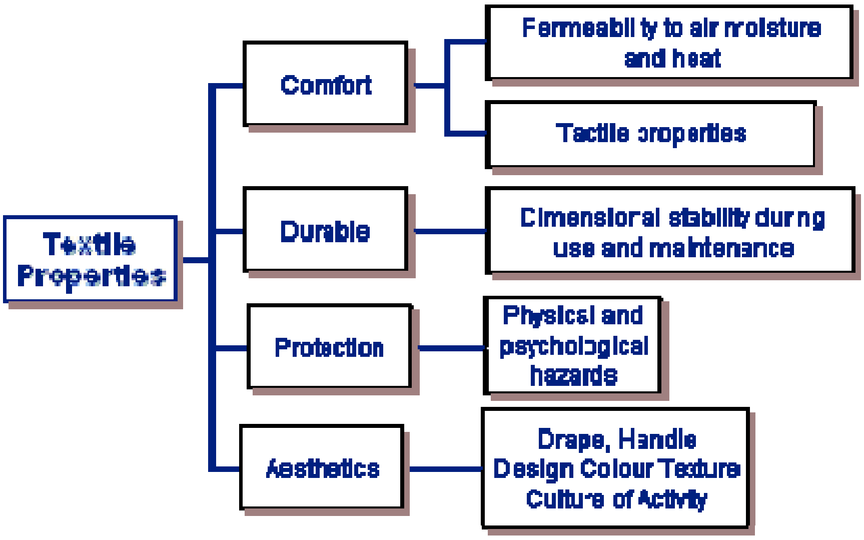

Figure 55: Core textile requirements for use in apparel

The primary function of a clothing system is to ensure the physiological needs of the wearer are met and the properties of the system are compatible with the demands of the activity and environment (see section 1.1.2). Ideally the system developed as a result of this work would fulfil the criteria in figure 55 and avoid limiting factors associated with the aesthetic and physical interference of any particular mechanism.

The work conducted in chapter 2 as part of the ‘comfort zone’ suggests that the ideal functionality of the textile system to improve the subject’s comfort would be to increase its permeability to air as the relative humidity in the microclimate reaches 50-55% and reduce permeability below that point.

Drawing upon the botanical structures studied in chapter 3, the most likely method would be the development of a bilayer structure. Although existing design solutions (active fibres and perforated composite textile) demonstrate significant limitations, an alternative solution may be that the mechanism is engineered into a yarn in a way that the length remains unaffected during actuation.

5.2 Concept:

Physiological comfort is highly dependant on the ability of the clothing system to renew saturated air from the microclimate. This can be achieved manually by the wearer who opens up vent structures incorporated into the design by using zips or fastenings. However, the individual may also fail to detect and respond until the sensation of discomfort is well established. It is possible to utilise the air resistance properties of the system’s textile components but these are currently unable to adapt to changes; it would be ideal if the textile itself could sense an increase in humidity and adapt its air permeability to prevent or defer the sensation of discomfort.

5.2.1 Structural factors effecting air permeability

The structural aspects that influence textile air permeability properties are illustrated in fig 56. Most fibres demonstrate a degree of transverse swelling during moisture sorption which leads to changes in fabric air flow resistance. Wehner et al (1987) studied the effects of swelling on the air permeability of textiles. A range of textiles were tested using an experimental apparatus that measured the air flow rate required to produce a specific pressure drop across a fabric sample, figure 57 compares the findings. It is evident that natural and regenerated fibres increase their resistance to air flow as they absorb moisture, while fabrics composed of synthetic fibres remain virtually unaffected. Wehner et al (1987) also found that the effect of hygral expansion was influenced by internal constraints (weave pattern, yarn twist etc) that affect the thickness and porosity of the texitle.

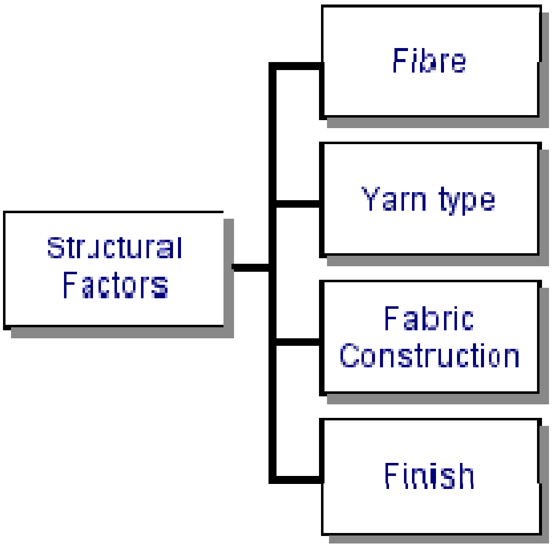

Figure 56: Structural factors effecting air permeability

Twist is required to lock short lengths of staple fibres into single ply spun yarns: the greater the twist the more compact the yarn. Crepe yarns are so tightly spun that they display a crimp along their length (Humphries, 1996). A textile made from crepe yarn will be less resistant to the passage of air than a sample made from a yarn of the same composition but with a less twisted yarn (Wehner et al., 1987).

The tightness of the structure is another important factor. This is determined by the area of fabric covered by yarn as opposed to air, known as the cover factor

(CF). The nature and structure of the yarn is closely linked to the CF, high twist yarns tend to be compact and cover less area than those with less twist or have other characteristics such as novelty structures (i.e. fancy yarns). In general terms, textiles with high CF are less permeable to air. In core spun yarns, both components (core and wrapping yarns) can affect the CF and effectively the permeability of a textile. A yarn composed of a filament core will result in a more permeable textile than a similar yarn made from a staple[47] core (Wehner et al., 1987).

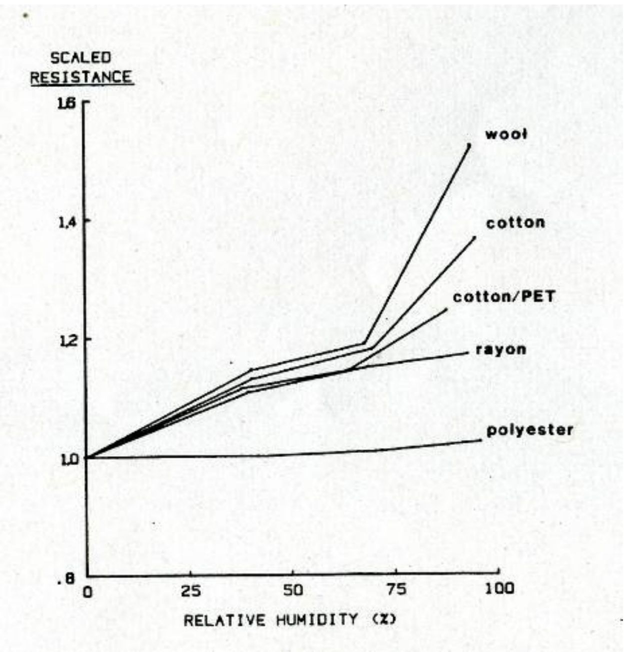

Figure 57: Effect of moisture absorption on air flow resistance (source: Wehner 1987)

The quantity of interlacing and pore size in woven structures also has a direct impact on air or wind resistance. Backer (1951) studied balanced[48] variations of 4 types of weave structure and found that plain weaves have most amounts of interlacing and smaller pores. This type of structure is likely to be less permeable to air than twill or satin weave (see appendix 4 for detailed structural variations of weave patterns) made from the same yarns, which have characteristic long floats and thus creating larger pores (Backer 1951).

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[47] A fibre of limited or relatively short length.

[48] A weave in which the average float is the same in the warp and weft directions, and in which the warp and weft floats are distributed between the two sides of the fabric (source: Textile terms & definitions 11th edition)

5.2.2 Adaptive yarn

The proposed mechanism illustrated in figure 62 has been informed by the outcomes discussed in chapters 1-4 and inspired by the botanical structures studied in chapter 3. Figure 62 depicts a yarn composed of active staple fibres that are fixed along one end to the core or main body of the yarn and have a free, protruding portion. In dry conditions (55% RH<), the loose parts of staple fibre curl or bend, increasing the width of the yarn. In damp conditions (55%RH>), the active fibres straighten aligning themselves with the axis of the yarn and thus reduce the width without affecting the length of the yarn.

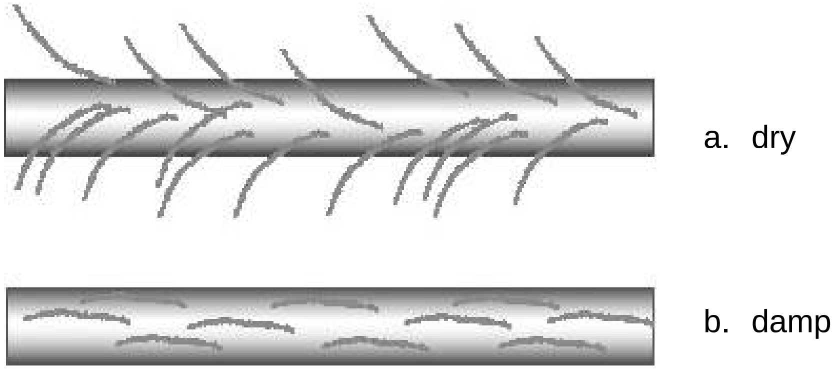

Figure 58: Yarn concept. In dry conditions (a.) the free part of the active fibres bend outwards increasing the width of the yarn by becoming ‘hairy’ in texture. In damp conditions (b.) the active fibres straighten and align with the axis of the yarn creating a smooth surface

The conventional behaviour of yarns made from most fibres is to increase the area of their cross section in damp conditions (hygral expansion). Although this is generally considered a problem in the clothing industry, because it reduces air permeability (causing discomfort) and dimensions of the textile, the reduction of inter-yarn spaces caused by the hygral expansion of cotton fibres can prevent water droplets from penetrating the clothing. This is a traditional method of introducing water resistant properties to clothing prior to the invention of membranes. Nylon fibres appear to be the exception as they demonstrate a negligible increase in air permeability in damp conditions (Gibson, 2002b).

Figure 59 proposes an application of the conceptual yarn into a woven structure.

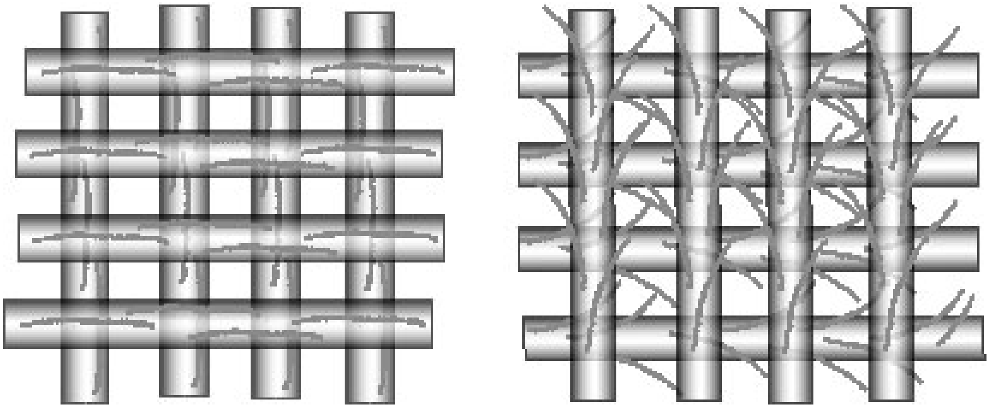

Figure 59: Possible application of adaptive yarn to woven textile system

5.3 Methods explored

The construction of the adaptive textile may be executed using several different methods illustrated in figure 60. The possibilities suggested are indicative and by no means exhaustive. Given the availability of resources, priority was placed on the identification of the simplest route that would deliver a prototype suitable for testing.

An active textile system with the functional profile described in section 5.2.2 could be realised in any textile structure (woven, knitted, nonwoven). The development of a bicomponent fibre was ruled out early on as there are no non-commercial bicomponent spinning facilities left in the Europe; the alternative was to create a bilayer composite material then slit it into filaments. This process is a standard commercial procedure and is used extensively for the manufacture of decorative metallic filaments and yarns such as those marketed under the Lurex [49] trademark.

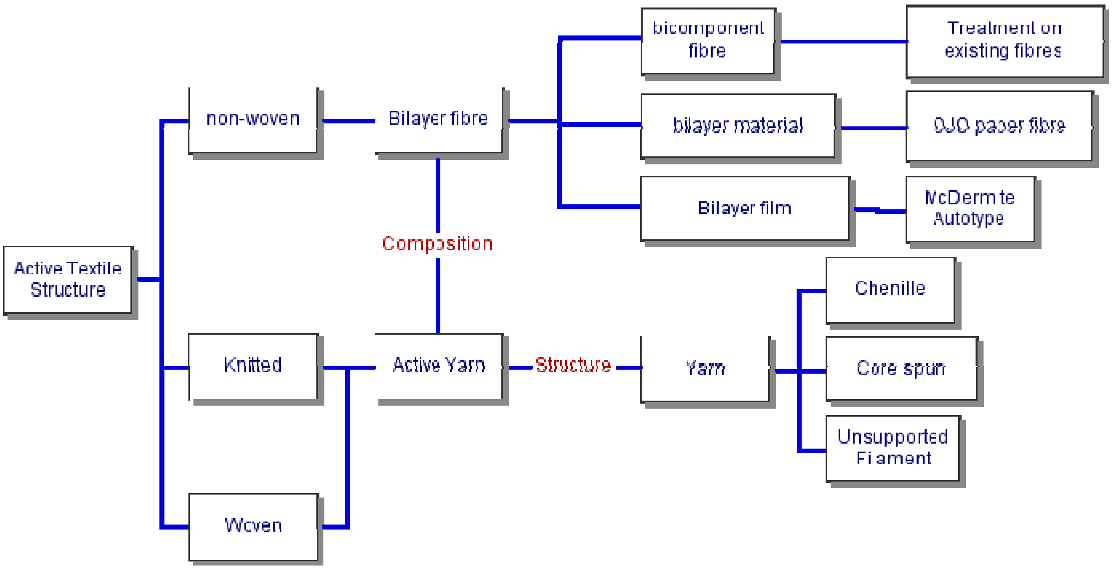

Figure 60: Development map – possible options

A potential material that seemed suitable for realising the concept was Japanese OJO+[50] paper yarn that had recently been developed for commercial use in the clothing sector. Sheets of paper made from Manila hemp fibres are slit into continuous lengths of filament fibre with diameters less than 0.8 mm then twisted into yarns suitable for weaving or knitting using a similar method to that used by Lurex[51]. It was assumed that the paper making process would enable the control of orientation of the manila fibres, therefore a bilayer material could be constructed using one layer of paper with fibres orientated along the length of the sheet and another with fibres orientated orthogonally, similar to the structure of the pinecone bract and bending legume studied in chapter 3. Twisting configurations would also be explored.

Preliminary experimental models were constructed using two layers of conventional lined notebook paper, stuck together using a solvent based glue

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[49] http://www.lurex.com/unsupported.html
[50] http://www.ojifiber.co.jp/e_paperyarn/e_process/e_process.html
[51] http://www.lurex.com/

(Copydex) (fig 66). Two configurations were selected, one using two layers of paper with fibres orientated at right angles to each other and a second using a layer orientated at ± 45^{o}. Upon wetting, the first model curled while the latter twisted; it is worth noting that the deformation was permanent and the models did not return to their original flat form upon drying, this was due to lower entropy in the shorter fibres.

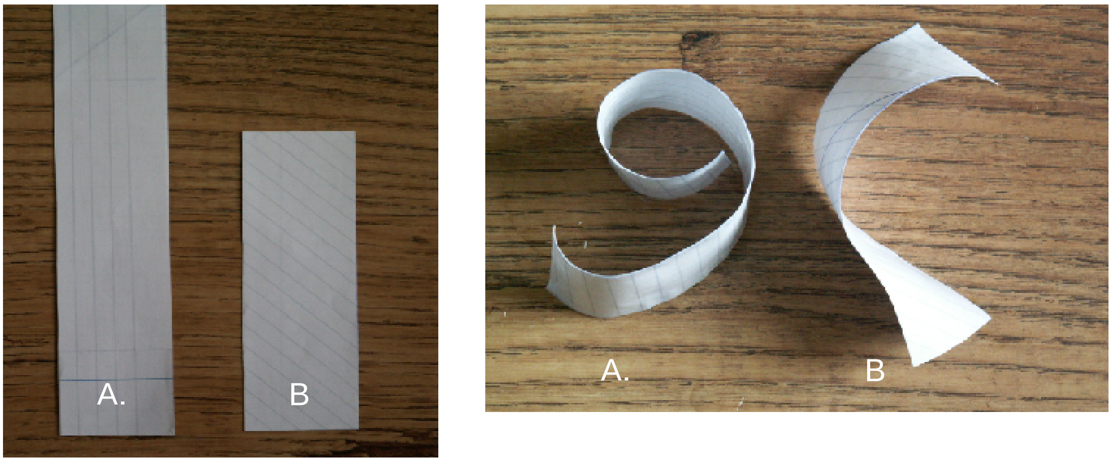

Figure 61: Experimental paper models. Left before wetting, right after wetting.

The optimal method for constructing a paper structure with two layers of different orientations of fibre was to use a dynamic former, a machine able to control the orientation of cellulose fibres during papermaking. The equipment was located at Manchester University, but had never been used. Despite several attempts, technical constraints prevented the creation of a successful paper structure.

An alternative method for creating a bilayer system was conceived, although it was not technically possible to create a paper with two layers of different fibre orientation, it may be possible to treat the fibres in one layer to alter their sorption properties, then introduce them into the composite structure. Samples of cotton and viscose fibres were sourced from Texter Yarns Ltd catalogue and OJO untwisted paper tape was sourced directly from Oji fibres ltd in February

2006 at Premiere Vision (a biannual textile trade fair held at Parc des Exposition in Paris).

Experimental Procedure:

Fibre samples were treated with solutions listed in table 5, the samples were washed with distilled water and left to dry in room with controlled temperature 25^o C and 40% RH. The single ply yarns were cut into 3 mm pieces with scissors that had been sterilised using Milton Steri-Wipes; 4 pieces of fibre averaging 0.9 mg in weight were placed in each balance of the Cisorp water sorption analyser. A treated sample was placed on one balance pan and an untreated sample on the other.

Sample	**Waterseal**	**Urea 5mol**	**Urea 8mol**	**NaOH 5mol**
Cotton	3min	6min	6min	6min
Paper Tape	3min	6min	6min	6min
Viscose	3min	2min	2min	NA

Table 5: Fibre sample treatments (top heading) and exposure times.

The isotherm experiments had 9 steps: adsorption 50% to 90%RH and desorption 90% to 50%RH. The chamber temperature was set at 22^{o}C. The cycle’s first step was at 50%RH. Relative humidity was increased by 10% till the RH value was 90% then decreased till the RH value was 50%. The mass change of the sample was measured every 3mins and the equilibrium condition was set to <0.001% total mass change within 60mins. The test took about 9 hours. Appendix 3 contains a full list of the experiments conducted with notes and observations of each test.

5.4 Results

The sorption behaviour of the untreated samples is compared in figure 62. Three types of cellulose were used: natural cotton cellulose, viscose made from regenerated cellulose and manila hemp cellulose in the form of paper tape recently developed for commercial use in textile yarns.

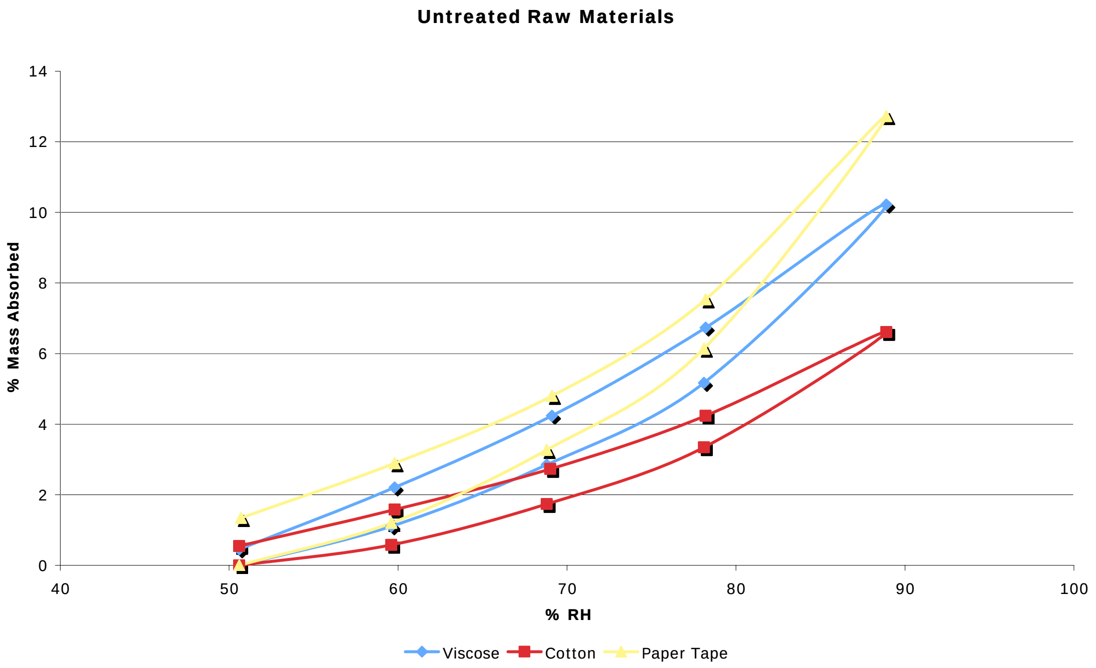

Figure 62: Isotherms of untreated samples. Yellow = paper tape, Blue = viscose fibres Red= Cotton fibres

It is apparent that the paper tape is more absorbent than the viscose and the cotton fibres. The differences in the moisture regain between the viscose and the cotton are due to the fact that regenerated cellulose fibres have more amorphous regions than cotton (Sheppard and Newsome, 1934, Segal et al., 1951, Okubayashi et al., 2004). The hysteresis demonstrated by the viscose covers a greater area than the cotton, and is mainly due to the less crystalline structure of viscose but may also be influenced by differences in the pore size and inner fibre surface (Okubayashi et al., 2004).

The making of manila tape alters the sorption mechanism in the material into a physical rather than chemical interaction (Seborg and Stamn, 1931, Sheppard and Newsome, 1934). Observations will be noted to identify similarities /differences in behaviour.

Cotton

The effects of the various treatments onto the cotton fibre are illustrated in figure 63. It is evident that treatment with 8M Urea increased the absorption properties more than any other and the Waterseal treatment reduced moisture regain.

Solutions of Urea and NaOH were used to reduce the amount of crystalline regions in the structure by breaking the hydrogen bonds that characterise the areas; this is a likely explanation for the increase of moisture regain. However, there is difference in the hysteresis, especially in the sample treated with 8M Urea, which is significantly reduced.

Treatment of fibres using 5M solution of Urea did not affect the overall percentage of mass change compared to the untreated sample; however, there is a significant reduction in hysteresis after treatment. This suggests that the 5M Urea solution prevents the fibre from retaining moisture during desorption. Results from work on botanical and man made fibres from the previous chapter indicate that the moisture most readily lost during desorption are the layers of water molecules that build up on the surface of fibres during the later stages of sorption. This effect is further amplified when cotton fibres are treated with 8M Urea solution. Although the percentage of mass change increases by approximately 65%, suggesting the dissolution of crystalline regions, hysteresis is severely reduced.

If hysteresis is caused by bound water trapped in the structure of the matrix, then the increase of amorphous regions in the fibre would explain the increase in retained moisture by the 5M NaOH and 8M Urea treated sample. Yet the cotton treated with 8M and 5M Urea demonstrate little retention of water compared to the other samples. Further research into the effect of the treatment of the fibre is necessary; it may be that the Urea is doing more than just dissolving the crystalline regions. Testing on a range of cotton samples with known history and comparing the results with NaOH treated and untreated samples would identify if this is the case.

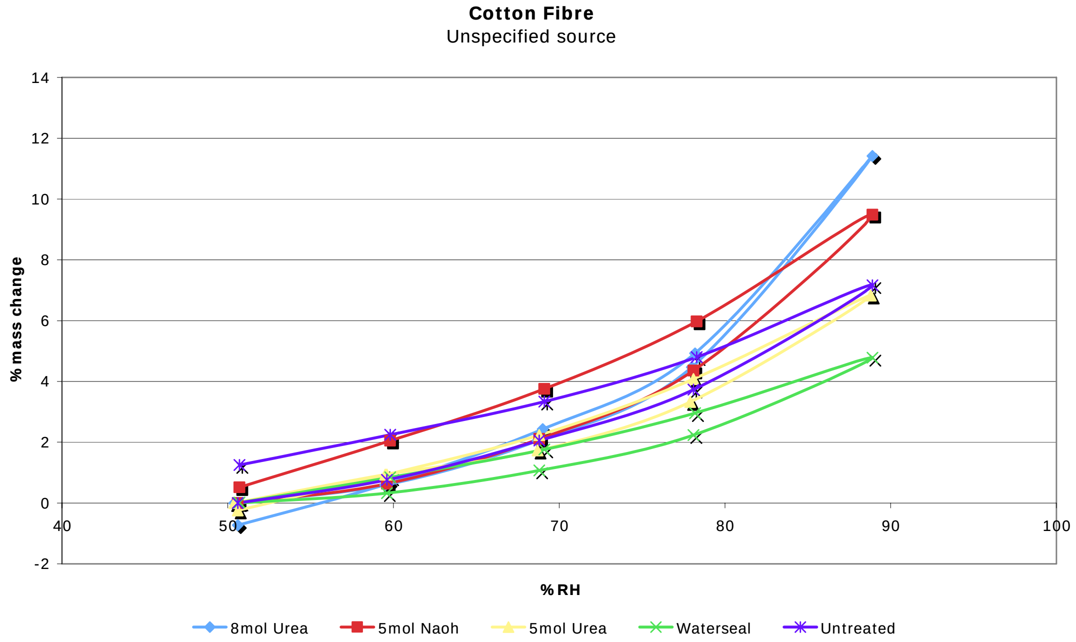

Figure 63: Isotherm of treated cotton fibres. 8M urea (pale blue) treatment both increases %mass change by 65% and reduces hysteresis to minimum. 5M Urea (yellow) treatment does not effect %mass change but reduces hysteresis. 5M NaOH (red) treatment increases %mass change by 35%. Waterseal treatment reduces % mass change by 30%

Waterseal is a silicon based compound designed for treating porous surfaces such as bricks and cement to prevent the penetration of moisture. This treatment reduced the moisture regain of the sample; however the hysteresis indicates that some moisture was retained within the system.

In order to create a bilayer paper type structure using cotton fibres that would perform in a similar way to the botanical materials studied in the previous chapter, it would be ideal to combine one layer of 8M Urea treated fibres with a layer of either untreated or Waterseal treated fibres.

Viscose

8 M and 5 M Urea treatments increased the moisture regain of the viscose fibres by 80% and 25% respectively while reduced the degree of hysteresis (fig 64). NaOH dissolves viscose rapidly and could not be used for the treatment of the viscose fibres. Treatment with Waterseal reduced %mass change by 15%. An ideal bilayer combination for the simulation of botanical bilayer systems is 8M Urea and untreated viscose.

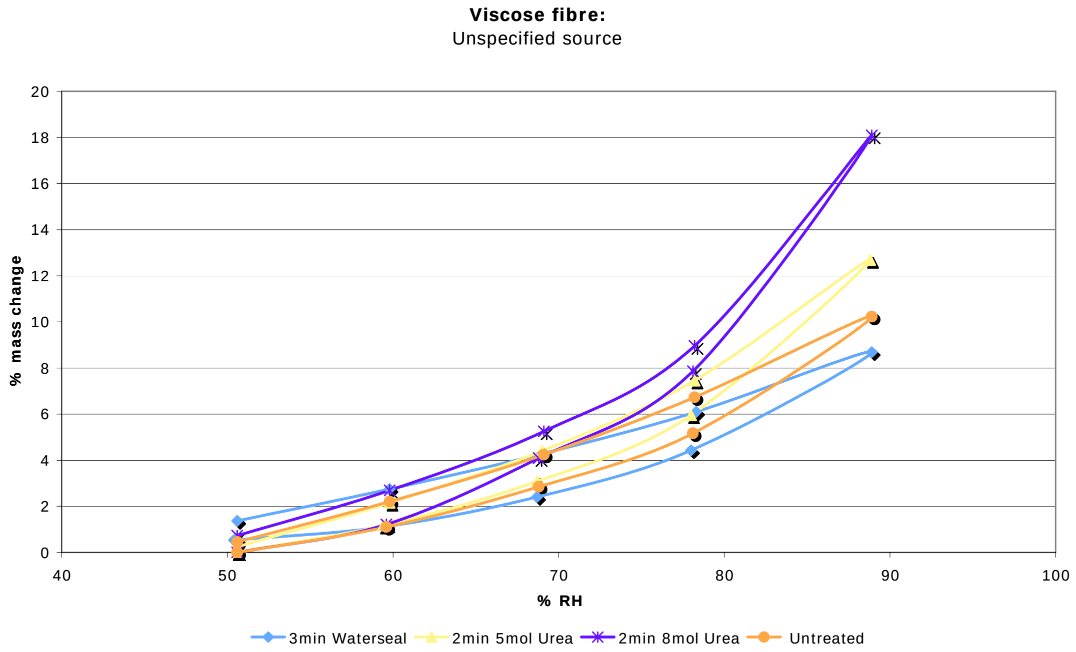

Figure 64: Isotherm of treated viscose fibre. 8 M Urea (purple) treatment increased %mass change by 80%, 5 M Urea (yellow) treatments increased %mass change by 25%, both reduced the degree of hysteresis. Treatment with Waterseal (blue) reduced %mass change by 15%.

Manila tape

The results from the paper tape were surprising, although the Waterseal treatment had a similar effect on the paper tape as in the other samples with an actual reduction in %mass change by 30%; the Urea and NaOH solutions had the reverse effect on the moisture regain properties; mass change was noted to be approximately 8% (8M Urea) and 15% (5M NaOH) less than that of the untreated sample (fig.65). However, both the urea and NaOH treatment reduced the degree of hysteresis. Sheppard and Newsome (1934) and Seborg and Stamn (1931) described a physical mechanism of sorption based on the fibre to fibre bonding. The treatment reduces the amount of bound water.

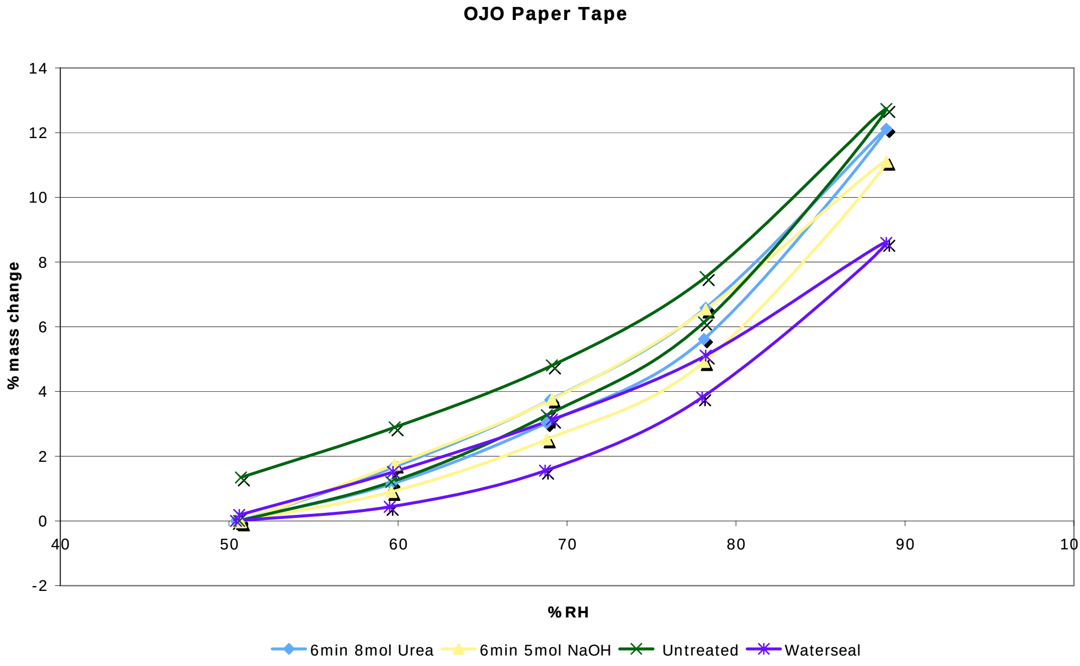

Figure 65: Isotherm of treated paper tape. 8 M Urea (pale blue) treatment decreased %mass change by 8%, 6 M NaOH (yellow) treatments decreased %mass change by 15%. Treatment with Waterseal (purple) reduced %mass change by 30%.

It is possible to alter the moisture regain properties of cellulose fibres by treating them with solutions such as Urea, NaOH or even chemicals used to damp proof buildings. Urea appears to minimise the hysteresis. The success of this method was founded on the assumption that it would be possible to create a custom bilayer paper structure using a dynamic former. The same technical constraints that prevented the creation of the paper model employing different fibre orientations obstructed the further pursuit of this idea.

The final option was the creation of a bilayer film; this route was enabled through collaboration with McDermite Autotype who specialises in the engineering and productions of thin films with a wide range of applications ranging from the print industry to reflective surfaces but have no experience in the textile sector. The progress of this route will be described in the next chapter.

Conclusion:

The aim of this chapter is to create a clear explanation of the methods followed and the role of each sector in this multi disciplinary project. The point of departure was a composite textile system developed in 1997 based on the moisture sensitive opening and closing mechanism of pinecones. Additional research into the requirements of the clothing industry, projected consumer expectations, perceived physiological comfort and hygroscopic botanical mechanisms helped hone the design brief and effectively the technological outcome of the work.

The proposed mechanism involves a moisture sensitive yarn able to alter its width without affecting the lengthwise dimensions and thus, when incorporated into a textile structure, the active yarn would manage the air resistance properties of the material. This chapter provides an account of the methods explored in an attempt to create a bilayer composite to mimic the behaviour of the botanical mechanisms from the previous chapter in order to incorporate them into the proposed yarn structure and the technical constraints that lead to the identification of the most suitable method. The next section will provide a description of the development process involved in the construction of the final prototype and its evaluation.

Chapter 6: Prototype development and evaluation

Introduction

The best method identified in the previous chapter was the creation of a bilayer film. Figure 66 illustrates the key objectives necessary for the transformation of a sheet of film into a textile prototype and the evaluation of its performance.

Figure 66: Film to prototype process map

This chapter sets out to describe the processes involved in the achievement of each of the objectives outlined in figure 66. The developmental work involved in the production of the bilayer film, technical issues encountered and evaluation is followed by an outline of the aesthetic design, set up and execution of the woven textile prototype is offered and finally the testing methods and evaluation are discussed.

6.1 Film development

The production and development of the bilayer film was carried out in the research lab at the MacDermid Autotype plant based in Wantage with the assistance of a team of scientists and technicians. MacDermid Autotype specialise in the development of thin films and coatings mainly for application in electronic, display screen, food and print industries. The research centre has facilities for developing small-scale samples from 1 to 30 cm ^{2} which can then be produced in larger quantities of hundreds of meters using a pilot machine.

The team at MacDermid had no experience with structural aspects of textiles although several of the company’s products are used in finishing processes such as textile printing. Consequently, the suggested combinations of cellulose for the chemistry of the bilayer film were limited to water-soluble options, due to the team’s expertise in cellulose coatings for the food industry. This however was deemed adequate for the purposes of this project, as the aim of the prototype is to assess the performance of the proposed mechanism.

The two types of cellulose proposed for the construction of the bilayer film were Ghosenolgh 20 (GH20), a type of polyvinyl alcohol for the swelling component and an ethylcellulose solution branded Hercules Aqualon r EC-N10 0100 by Ashland Inc for the non-swelling component.

6.1.1 Mayer rod method

In order to create a bilayer film we prepared an 8% solution of GH20 (obtained from a commercially available 16% version using distilled water) and a 5% solution of Aqualon r EC-N10 0100 was created from powder using Dowanol PM (by Dow Chemicals) solvent. A Mayer rod coater was used to spread each layer of the film. This is a stainless steel rod that is wound tightly with stainless steel wire of varying diameter. We used wire size 55 the specification of which can be found in appendix 5.

First a layer of GH20 was applied onto Makrofol DE 1-1C 175, this was used as the base for the construction of the film (this is a MacDermid product and was selected because it is a sturdy 375 µm film with a removable 40 µm layer), directly onto the removable layer. The single layer film was placed in an oven at 90oC to dry for 120 s, and then cooled in 25^{o}C and RH 45%. The same procedure was followed to apply the Aqualon solution, but it was left in the oven for 480 s.

The films created were approximately 15µm thick but the use of this type of viscous chemical with the Mayer Rods produced uneven surfaces. Therefore it was not possible get an accurate reading for the thickness of each layer.

Observations:

Visual observations were conducted using the controllable humidity of Cisorp chamber. Three film samples were fixed at one end to a piece of Blutak and placed inside the analyser's chamber. The chamber temperature was set at 22^{o}C and the humidity controlled using the apparatus software. The film samples were straight between 40-50% RH and curled in the direction of the Aqualon layer above 50% RH and in the opposite direction with RH below 40%. Although it is possible that the curling may be influenced by factors created during the drying and cooling process (Chow and Penwell, 1976) for the purposes of this study, it is more important to explore the structural parameters of layer thickness.

The moisture induced changes in curvature observed is similar to that of a bimetallic strip. The effect of material properties and dimensions on curvature of a bi-material strip is given through the equation[52]

$$\kappa = \frac{6E_A E_B (h_A + h_B) h_A h_B \Delta\varepsilon}{{E_A}^2 {h_A}^4 + E_A E_B {h_A}^3 h_B + 6E_A E_B {h_A}^2 {h_B}^2 + 4E_A E_B h_A {h_B}^3 + {E_B}^2 {h_B}^4} \qquad \text{(a)}$$

where E_A, E_B are the young's Moduli, and h_A h_B the thickness of the two materials A and B. The misfit strain $\Delta\varepsilon$ is given by

$$\Delta\varepsilon = (a_A - a_B)\Delta T \qquad \text{(b)}$$

where a_A and a_B are the coefficients of thermal expansion of the two materials. Dawson et al (1997) adapted equation b by altering the a_A and a_B with the coefficients of hygroscopic expansion.

It is clear from equation a that curvature κ is clearly linked to the stiffness of the two materials, but more so to the thickness of each layer as h_A and h_B are used

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[52] http://www.doitpoms.ac.uk/tlplib/thermal-expansion/bimaterial-strip.php

in powers of 2,3 and 4 in equation a. Any increase in layer thickness of either layer will cause curvature to decrease and vice versa.

The combination of the Mayer Rod method with the viscous nature of the chemicals used to compose the bilayer film proved to be problematic as it was not possible to create homogenous layers or accurately measure the thickness of each layer. In order to study the effect of layer thickness experimentally the use of a spin-coating machine was identified as an alternative construction method.

6.1.2 Spin-coating method

A 6, 5% solution of Hercules Aqualon EC N200 (Ashland In)c was created from powder using Dowanol PM solvent (Dow Chemicals). A solution of Ghosenol GH20 16% was used in its commercially available diluted form. Circular discs with diameter 15cm were cut from Makrofol DE 1-1C 175 (McDermid).

Speed/ rpm	Aqualon N200	GH20
1000	8.2 μm	N/A
2000	5.9 μm	15.3 μm
3000	3.9 μm	10.6 μm
4000	3.4 μm	8.9 μm
5000	N/A	N/A
6000	N/A	5.4 μm

Table 6: Table of film thicknesses achieved at different spin speeds for both Aqualon N200 and GH20 solutions

Single layer films were initially created to measure effect of speed on film thickness; table x lists the variations. Small quantities of solution were placed in the centre of each Macrofol disc then set the spin coater [SPS (Semiconductor Production Systems) model: SPIN 150 wafer spinner] to run for 60 seconds at a variety of speeds. A fine cross section of each film was obtained using a microtome (Leica model: RM2145 Microtome) and the thickness of each film was measured using a microscope. Figure 67 depicts the cross section of a Aqualon N200 sample that was spun at 1000 rpm for 60 seconds, the removable 40 µm film of the Macrofoil is also clearly visible (see appendix 6 cross section images of other films).

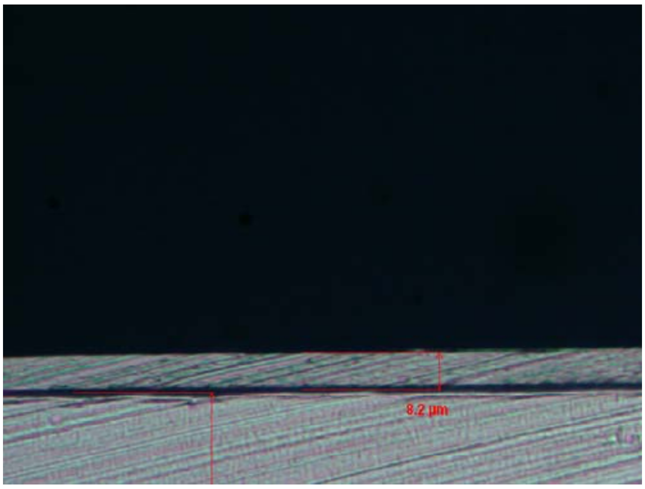

Figure 67: Cross section of film made from Aqualon N200 at 1000 rpm 50x. The 8.2mm film (top layer) positioned on the surface of the 40mm removable film of the Macrofoil.

The range of bilayer films created using the spin coating apparatus is listed in table 7. The same measurement method was used to verify the thickness of each layer; the resulting film thicknesses are illustrated in table 8 and 9. The inconsistency in thickness between the same speed layers is believed to be due to the highly viscous nature of the solutions. For the purposes of this project though, each bilayer film will be treated as a composite structure and priority is placed on the performance evaluation of each film in terms of curl behaviour to identify the most suitable combinations for use in the prototype.

Film	Aqualon EC N200/ rpm	GH20/ rpm
1	1000	2000
2	1000	3000
3	1000	4000
4	1000	6000
5	2000	2000
6	2000	3000
7	2000	4000
8	2000	6000

Table 7: Range of composite films

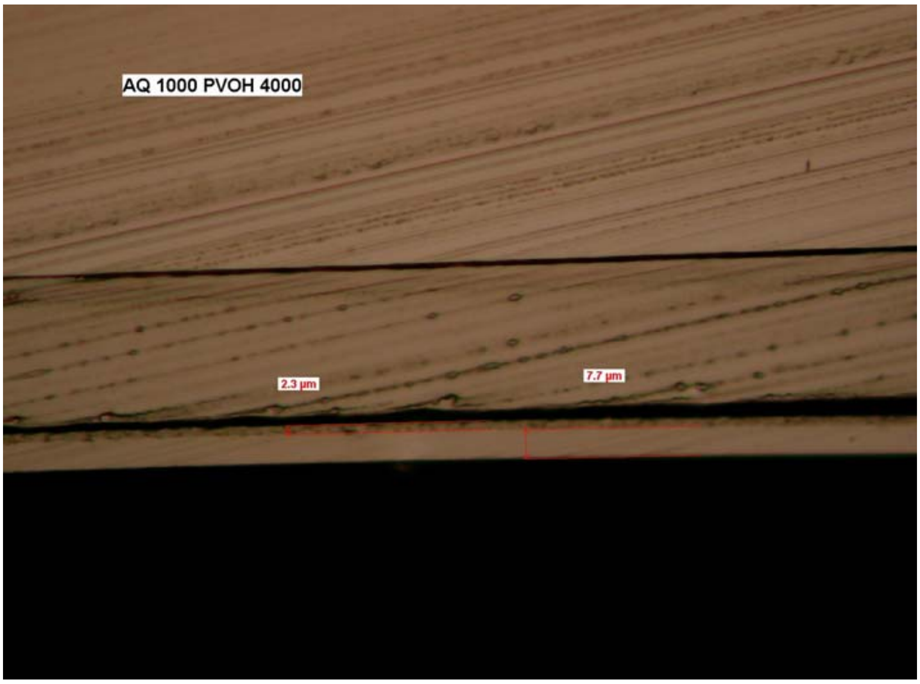

Figure 68: Cross section measurement of Aqualon N200 1000 rpm GH20 4000 rpm

AQ1000		
8.2 µm	10.3 µm	PVOH 2000 rpm
9.1 µm	4 µm	PVOH 3000 rpm
7.7 µm	2.3 µm	PVOH 4000rpm
6.2 µm	4.8 µm	PVOH 6000 rpm

Table 8: Thickness of AQ N200 at1000rpm film range

AQ2000		
3.1 µm	15.4 µm	PVOH 2000 rpm
3.4 µm	9.7 µm	PVOH 3000
5.5 µm	10.3 µm	PVOH 4000 rpm
3.2 µm	5.2 µm	PVOH 6000 rpm

Table 9: Thickness of AQ N200 2000rpm film range

6.1.3 Film evaluation

Three jars were used to create controlled conditions of relative humidity. One contained silica to achieve the driest microclimate (approximately 9%RH), while saturated solutions of sodium bromide and potassium sulphate where used to create conditions around 55%RH and 80% RH respectively. 4 X 10 mm samples of each film were cut and mounted onto a paperclip as illustrated in figure 69a. Table 10 lists the internal temperature and humidity of each jar. Each sample was individually mounted and inserted into a jar and left to calibrate for 30 mins. The distance between the secured edge of the film and the loose end were then measured; the larger the measurement the less the curvature (Fig 69b). Two samples from each film were tested; the results for each film type are illustrated in appendix 7.

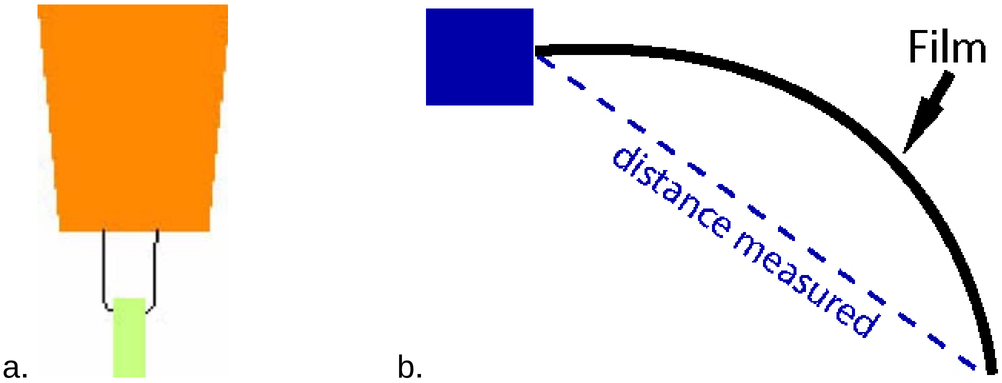

Figure 69: a. Diagram of film sample mounted on cork b. Distance measured at each humidity

The bilayer films were created in conditions similar to the external conditions of this test, this is why bending behaviour was noticed at both higher and lower humidity, and the films were straight in external conditions. The least curvature was noticed in the films that were coated with a thin layer of GH20 approximately 5μm. However, most samples were easily damaged when exposed to high humidity and therefore would not repeat their behaviour. This is due to the nature of the chemicals used which were water-soluble. The most resilient samples that did not damage and demonstrated repeatable curling behaviour were Aqualon N200 3.1μm / GH20 15.4μm (fig 70) and Aqualon N200 5.5μm / GH20 10.3μm (fig 71).

Salt Solutions Humidity Check 20/07/07		
	%RH	^{o}C
External	45.8	26.4
Silica	8.5	28.6
Sodium Bromide	55.4	28.4
Potassium Sulfate	80.3	30.4

Table 10: Humidity and temperature measurements

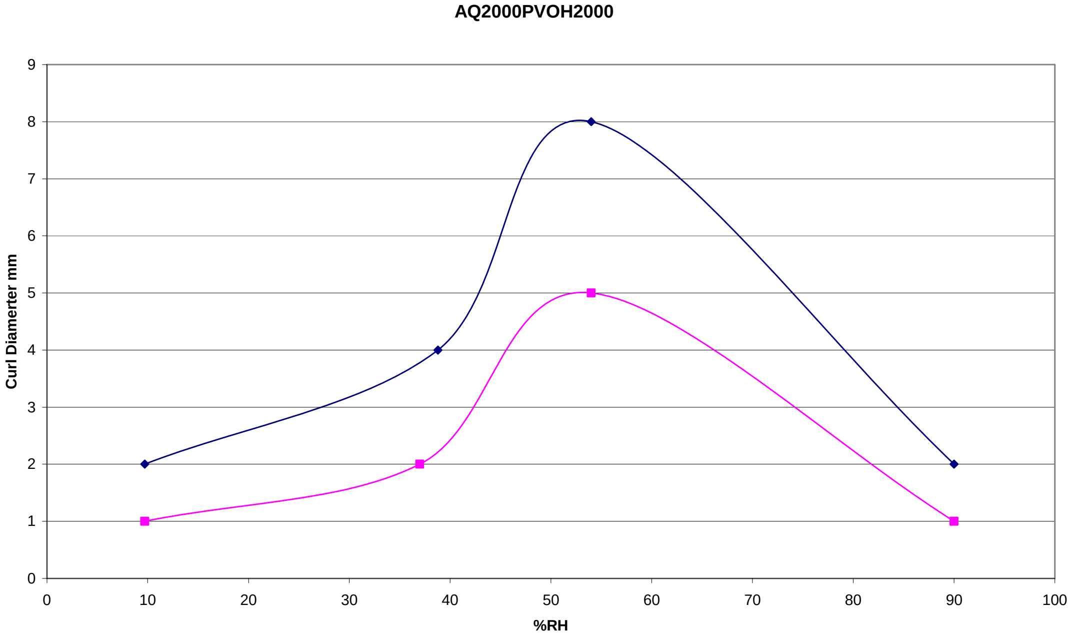

Figure 70: Aqualon N200 3.1μm with GH20 15.4μm

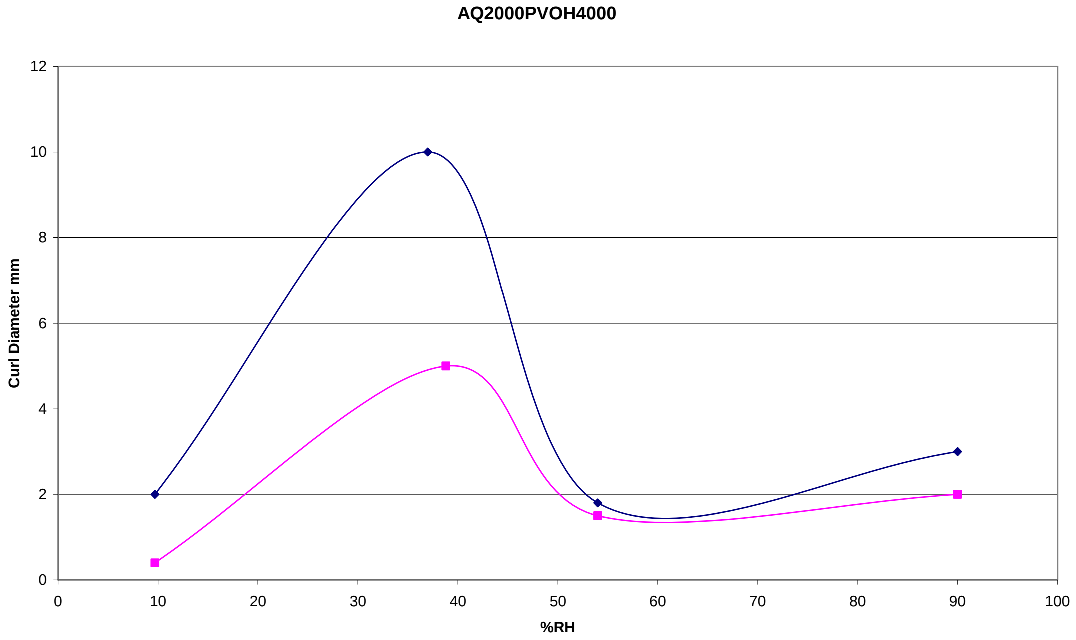

Figure 71: Aqualon N200 5.5μm with GH20 10.3μm

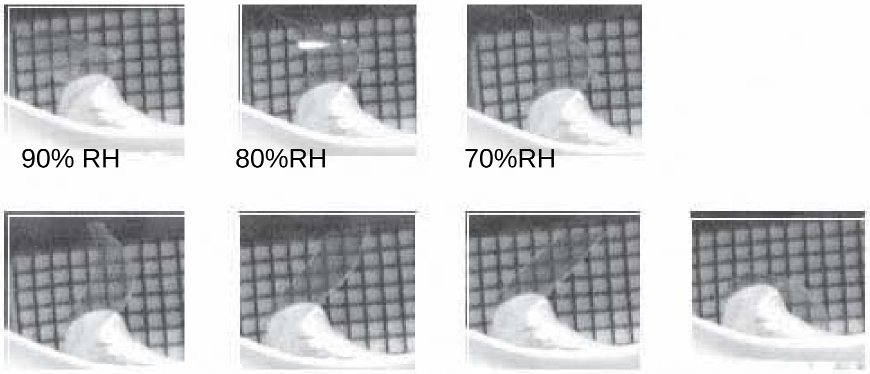
90% RH
80%RH
70%RH
60% RH
55%RH
50%RH
40%RH

Figure 72: Aqualon N200 3.1μm with GH20 15.4μm. The film curls in both directions, in higher humidities it curls in the direction of the Aqualon, becomes straight 50-55% RH then curls in the direction of the GH20 in drier conditions.

The two film types were further observed using the controlled chamber of the sorption analyser. The samples were cut into 10mm X 4mm strips and mounted onto a base using Blutak (figure 72). The samples were then exposed to several cycles ranging from 40-90% humidity were repeated for each film type to identify the most resilient and reliable. The most suitable film sample was the

Aqualon N200 at 2000 rpm with GH20 at 2000 rpm. 25 meters of this film were reproduced using MacDermid Autotype’s pilot facility.

6.2 From film to unsupported monofilament yarn

The film produced by MacDermid was approximately 25m long and 40 cm in width, the yarn proposed in chapter 5 requires the slitting of the film into finer filaments. This step can be achieved using standard technology applied in textiles for many decades; a key company whose product range is based upon this method is Lurex Company Ltd (UK). Metallised and iridescent polyester films that range from 12-40 µm in thickness are slit into fine filaments whose diameter can vary from 0.25 – 0.8 mm. These continuous strips of film are used directly as monofilament yarns and can be supported (i.e. twisted with another filament yarn for extra strength) or unsupported[53]; the latter format is relevant to this development.

The Lurex Company Ltd Research and Development Laboratory based in Leicester agreed to process the film produced at the MacDermid plant. Figure 73 illustrates the slitting process. The width of a roll of film can vary between 1-2 m wide; this is sliced into approximately 25 mm sections using a primary slitter. The slit film is then passed through ‘micro’ or ‘fine’ slitters that further cut the film into narrower strips that can vary from 0.25-0.8 mm in diameter. Lengths of slit film are joined together with heat activated splicing tape made from either nylon or polyester tape to create long, continuous filaments.

The research team at Lurex initially processed a test film produced using the spin coater. The film was sliced into 0.25 mm wide filaments successfully using a small-scale slicer. This demonstrated that it was possible to process this particular film whose physical properties varied greatly from those the team are used to handling.

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[53] http://www.lurex.com/unsupported.html

The final film supplied was originally 40 cm wide and 25m long. The primary slitter cut the film into strips 54 mm wide, which were further processed by the micro-slitters into 0.8 mm filaments and wound onto bobbins. It was not possible to recreate 0.25mm filaments on standard machinery.

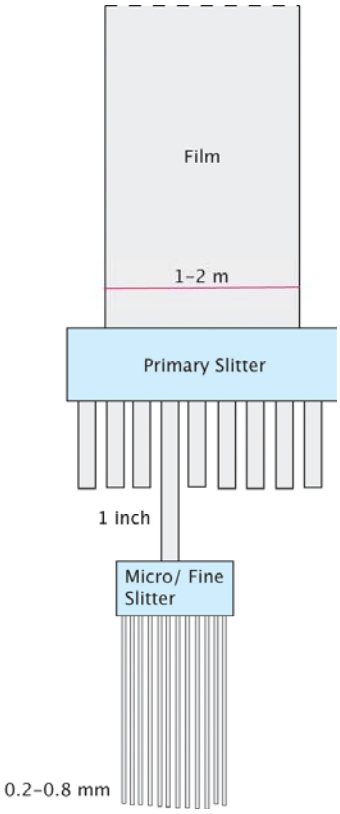

Figure 73: Slitting process

The technical team experienced several difficulties in processing the film on the standard machinery. Firstly, they found that the length we supplied was not long enough to run through the process path. In addition, the curling of the film created difficulties in handling as well as the application of adhesive tape to join lengths together. Finally, the team found that the antistatic spray, normally used on standard commercial films, caused the experimental film to dissolve. Despite these difficulties, it was possible to slice the film in to 0.8 mm filaments suitable for use in a textile structure.

6.3 Textile construction

The technical difficulties experienced during the slitting process by the team at Lurex made the construction of a chenille type yarn impossible because a 0.8mm strip would be too wide to achieve the desired effect. A radical rethink of the prototype design was necessary. Instead of creating a composite yarn incorporating the bilayer filament, the strips themselves were wide enough to be used as a monofilament[54] yarn. This type of yarn (known in the textile industry as unsupported monofilament yarns) is commercially available and used in many types of knitted and woven textiles. Due to their low tensile strength, unsupported monofilaments are not used alone in the warp but introduced mainly in the weft of woven textiles.

A new woven structure was designed to host the adaptive monofilament yarn. The equipment, technical support and studio space necessary for this stage of the development were provided by the Textile Department at Chelsea College of Art and Design, part of the University of Arts London.

The design of the textile was based on leno weave methods because it offers better structural support to the active monofilament than a simple or plain weave pattern. Leno is a form of weaving in which the warp threads are made to cross one another between the picks (Denton and Daniels, 2002), although there are several methods for creating this effect, in this case a doup (white yarn attachment in fig 74) was used.

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[54] Yarn consisting of a single filament

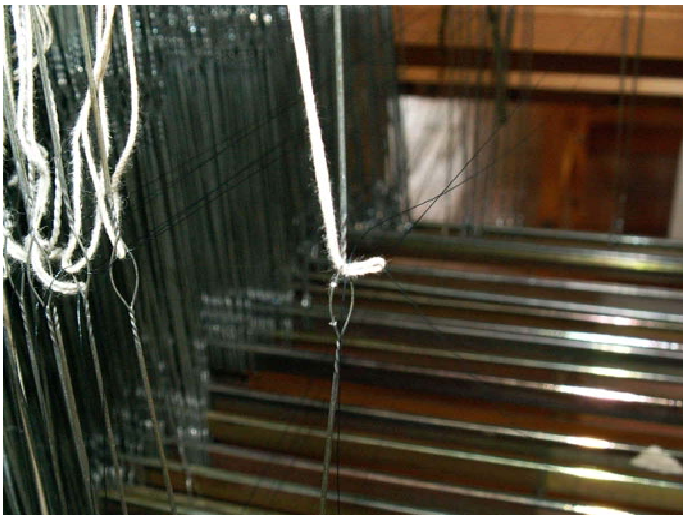


Figure 74: Leno weave doup

Executed in yarn pairs, alterations in the shaft lift patterns cause the one yarn to loop over the other. Leno weave methods are conventionally used to create open structure fabrics including some gauzes and muslins. Also, leno pairs are often added to the edges of woven fabrics (selvedge) to prevent the structure from fraying. The structural advantages of leno weave make it an ideal system to base the design of the prototype; figure 75 illustrates some visual sources of inspiration that informed the design of the final samples.

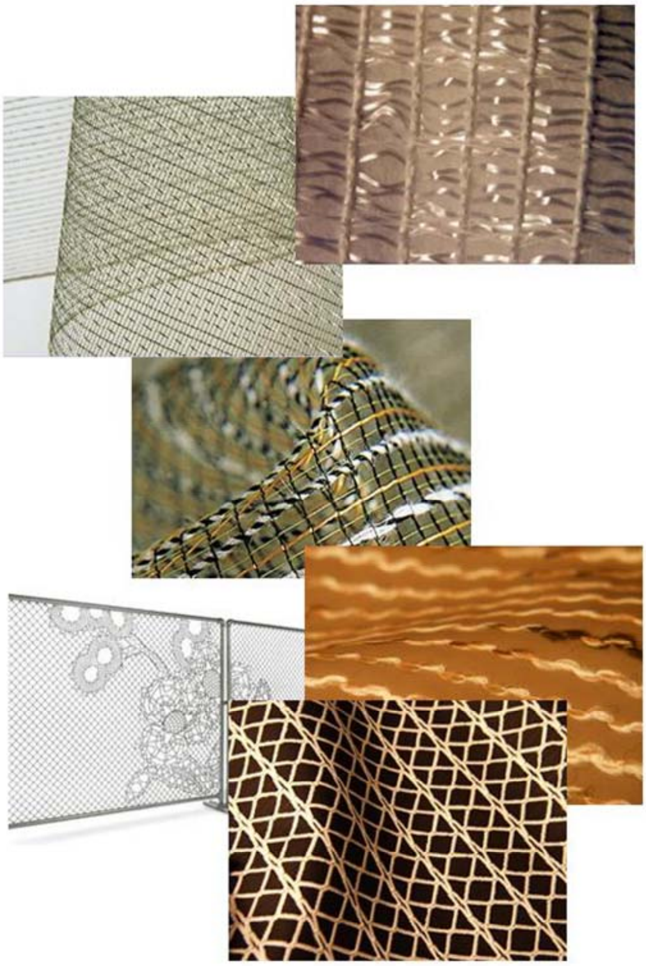


Figure 75: Examples of design inspiration

Method:

Two designs were selected for the final prototypes; one pattern is illustrated in figure 76. Each row represents a shaft and each column an end (represented by ‘x’). The leno pairs are threaded in the two rear shafts and brought together in shaft 1 and 2 where the doup (fig 89) is located. The leno doup is symbolised with an ’o’. The design includes a leno pair at the selvedge, followed by a ¾ inch section of plain weave, 3 leno pairs and another section of ¾ inch plain weave. This is repeated across the width of the sample. The second pattern is a variation on the first (a series of independent leno pairs are secured between two sections of plain weave).

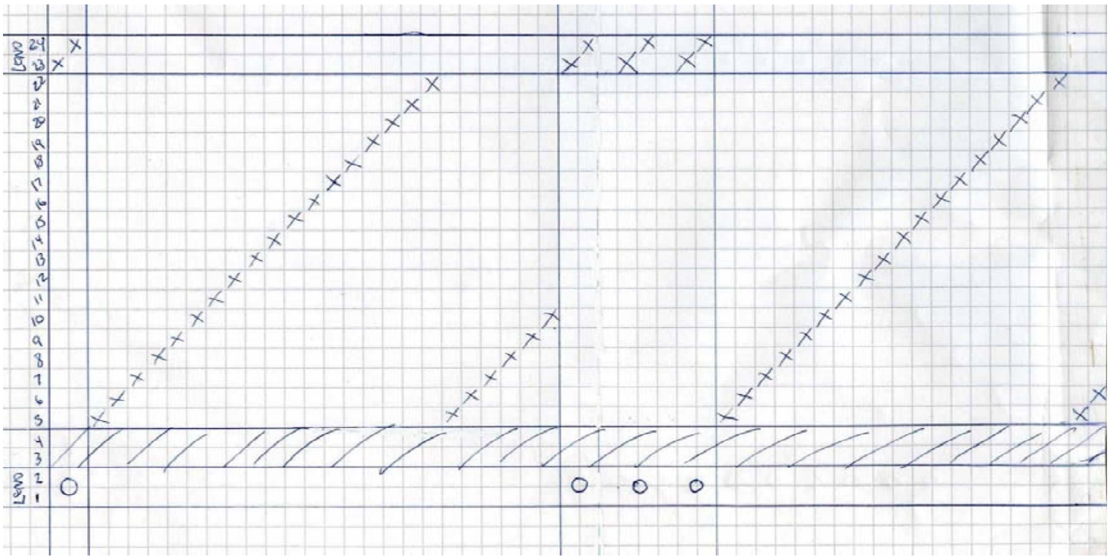
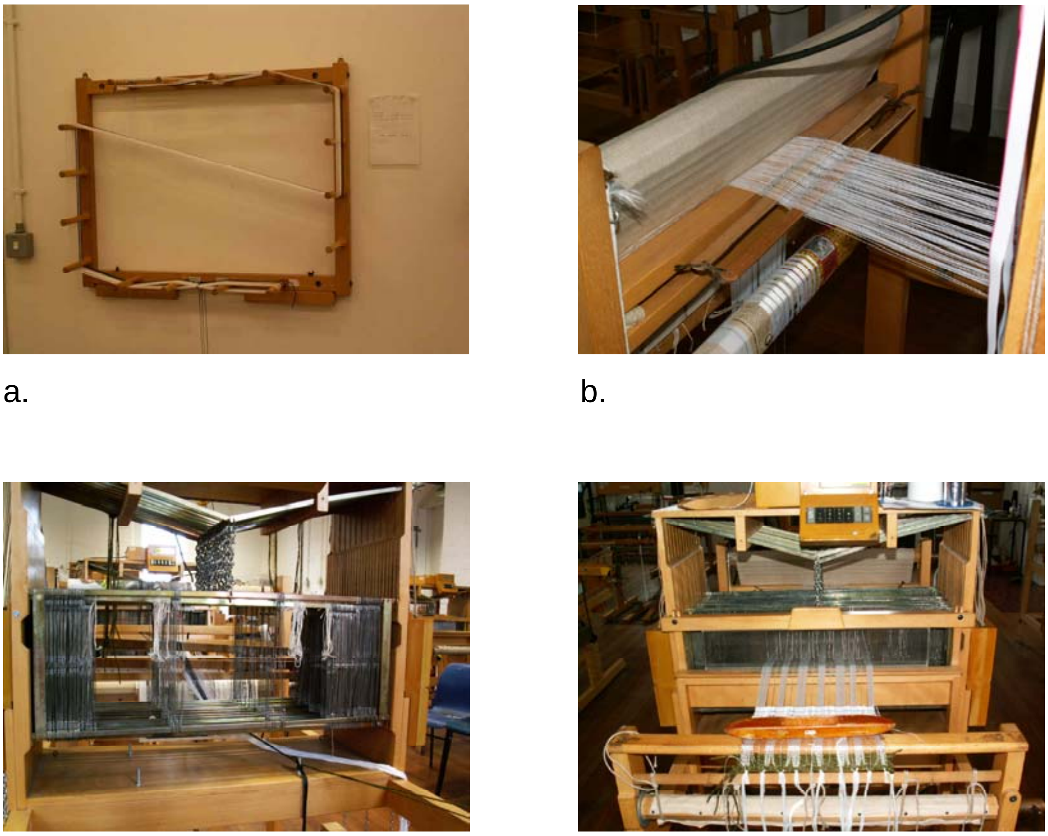


Figure 76: Weave pattern plan. Numbers on left represent each shaft. X represents hedles per shaft that need to be threaded. O symbolises position of doup at which point ends (yarns) threaded through shaft 23 and 24 are paired to create leno weave.

The set up of a loom is a standard process; the basic stages are illustrated in figure 77, this is an indicative, not a detailed account of the process. A 100% polyester two ply yarn measuring 40 ends/inch was used in the warp of the prototype. Figure 77 a. depicts the preparation of the textile's ends. These are then transferred to the back of the loom and each end is threaded through a single heddle eye fig 77 b and c, the ends are spaced according to the design through the reed (fig 77 d), finally the loom shafts are programmed to lift according to the design. The weft yarns are laced into the structure using a shuttle (fig 77 d); the active monofilament and two ply polyester yarn were wound onto bobbins suitable for use in a shaft.



a. b.

c. d.

Figure 77: Loom set up process

Figures 78 and 79 are images of the resulting textile structures; the active monofilament is clear and therefore difficult to see or record photographically. The next section will evaluate the performance of the textiles.

6.4 Prototype performance evaluation

The desired functionality of the textile as described in chapter 5 is the ability to alter its resistance to air in response to changes in atmospheric moisture. Visual observations of the samples using the controlled humidity chamber of the Cisorp sorption analyser revealed that the cross section of the active monofilament yarn curled inwards resembling a cigar shape reducing the width of the yarn from 0.8mm when flat to approximately 0.3mm when curled as a result of increase in humidity. This in turn increased the pore size of the structure and effectively the permeability. In order to verify this functionality it was necessary to identify a suitable test method that would measure the effect of changes in relative humidity on the permeability of the structure.

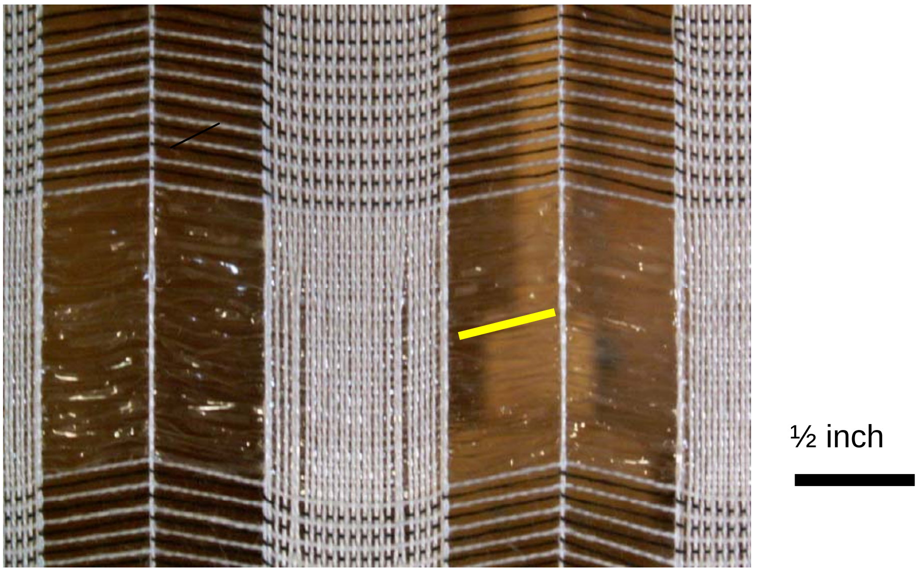


Figure 78: Close up of weave pattern 1 prototype. The clear strips are the bilayer film highlighted with yellow line

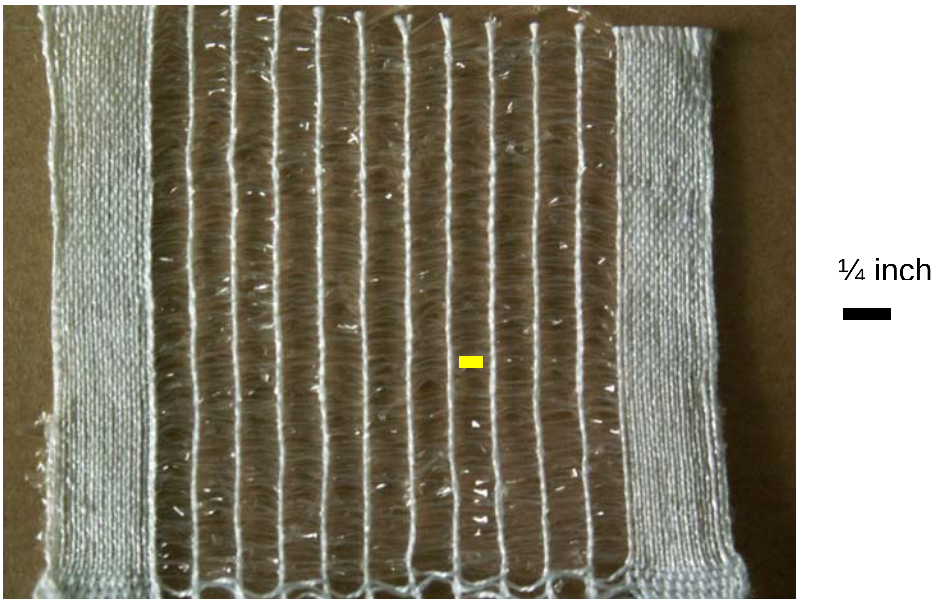


Figure 79: Close up of weave pattern 2 prototype, the transparent areas are the active yarn, indicated with yellow line

Standard air permeability tests on clothing textiles are conducted in controlled environments using a set temperature and relative humidity; the testing procedure is defined in BS 5636. Wehner et al (1987) found changes in convective gas flow properties of textiles caused by fibre swelling(Wehner et al., 1987) while Gibson et al (1999) developed experimental tools and methods to study the effects of moisture on the air permeability of woven and non-woven textile materials. The testing apparatus (fig 78) created by Gibson et al (1997) was used to test the performance of this prototype.

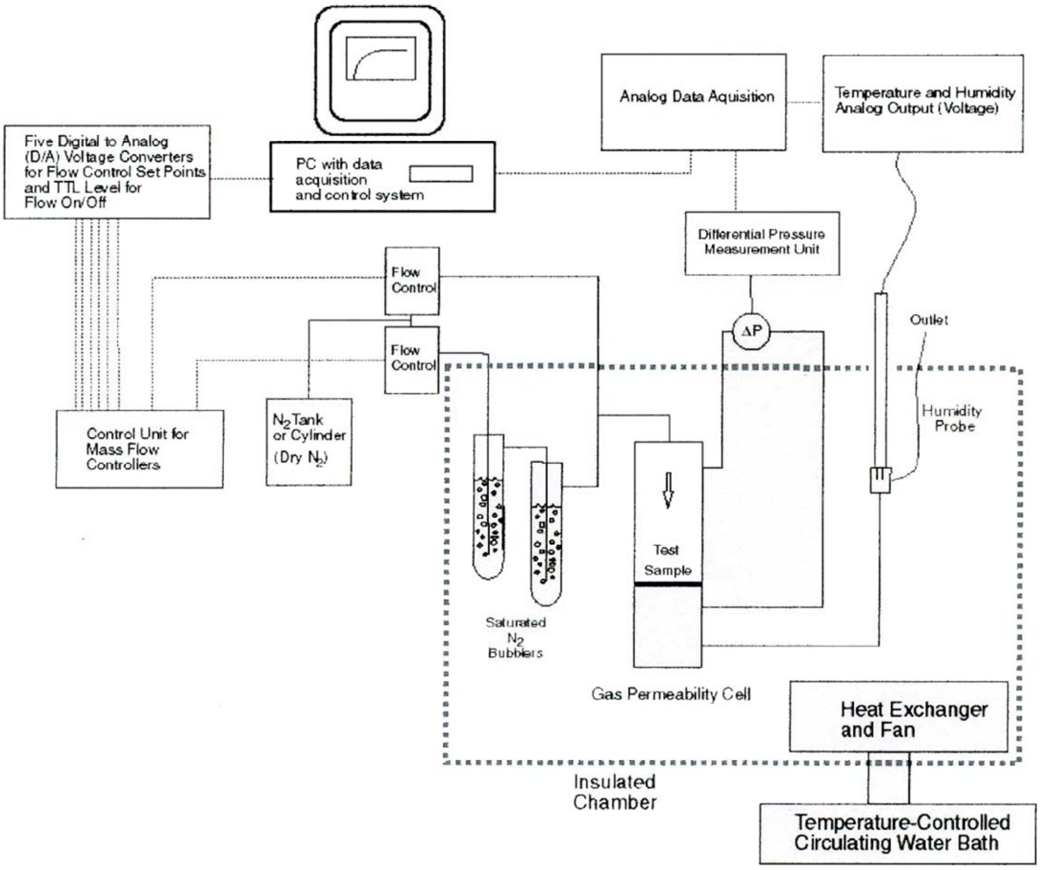


Figure 80: Diagram of testing apparatus [source:(Gibson et al., 1997)]

Method:

Experimental procedure is defined in Gibson et al (1997); samples were clamped onto test rings as shown in figure 80a. The test sequence was set using a computer interface fig 80c. Set points of 4 h were programmed for each relative humidity (default setting of 0.0, 0.2, 0.4, 0.6, 0.8, 0.9., and 0.95) and the temperature was set at 30 °C. Gas Flow Rate was set at 2000 cm^3/minute and sample diameter was 2.5 cm with an area of 0.0004909 m^2. Given the sensitive nature of the active film the highest relative humidity was programmed at 95% to avoid damaging the sample. Figure 81 provides photographs of the testing apparatus with the textile prototype.

6.5 Results

Air permeability is related to fabric geometry (Yoon and Buckley, 1984). Visual observation of the textile prototype at different humidities show the structure changing it's geometry, the flat ribbon-like monofilament yarn with a width of 0.8mm at 50-60%RH that transforms into a cylindrical shape with 0.3 mm diameter at higher humidity. The increase in pore size caused by the shape change in high humidity should cause a decrease in air flow resistance. This behaviour is counterintuitive; all know hygroscopic textiles (those made from wool, cotton, silk and other natural fibres) increase resistance to airflow as humidity increases.

The initial test following produced results that indicated no change in air permeability at the different humidity set points, this was due to the fact that the sample was clamped onto the rings very tightly, which is necessary for the testing of conventional textile structures. However, the tension created across the width of the sample prevented the monofilament to alter its shape. The clamps were released slightly and the sample retested, the results are illustrated in figure 82.

The results show the prototype structure demonstrates a decrease in air-flow resistance. The correlation coefficient is calculated at $r = -0.86$ indicating a strong downhill linear relationship between decrease in airflow resistance and increase in relative humidity.

This specific design reduces its resistance to air flow by approximate 20% at 80%RH, although the structure is porous by nature due to the scale of the prototype. Dr Phil Gibson commented that the effect can be increased if multiple layers of the structure were combined.

Two additional woven textile samples were tested using the same protocol with the prototype; one was made from 100% cotton the other 100% Nylon. We know that textiles made from hygroscopic fibres increase their resistance to airflow as they absorb more moisture, as fibres swell the yarn becomes 'fatter' thus reducing the size of the gaps between the yarns, while synthetic fibres remain unaffected. One minor exception has been noticed with woven Nylon textiles, the fibres increase in length when damp as opposed to diameter (they become longer rather than fatter), this can result in a nominal reduction in airflow resistance.

The cotton sample (fig 83a) demonstrated a gradual increase in resistance until 60%RH, as environmental moisture creeps above 60%RH, the resistance increased quite sharply. One explanation based on the observations noted in chapter 3 (fig 42) may be that in the lower humidity, moisture is adhering to the microfibrils in the fibre's amorphous regions, causing a gradual swelling of the fibre, above 60%RH moisture builds up in the capillary spaces between fibres pushing them further apart thus causing the yarns to swell significantly, which in turn causes the airflow resistance of the textile to increase at a greater rate than in the lower RH.

The nylon sample functions in a very different way, the test results (fig 83b) show a nominal increase in airflow resistance until 40%RH, above that point, resistance decreases till 80%RH where it reaches the original air flow resistance. Nylon fibres are known to increase in length as they absorb moisture, in this case, length increase commences at 40%RH, this causes minor changes to the samples dimensions that increase its porosity and create a structure that demonstrates the same air flow resistance at both high and low humidity.

Both cotton and nylon samples demonstrate high air flow resistance, cotton would be the most comfortable to wear as its hygroscopicity functions as a ‘buffer’ that will retain the microclimate moisture content low for a period of time determined by the wearers activity. Soon after he/she begins to perspire, the swelling fibres will increase the textile’s air flow resistance trapping saturated air in the microclimate that will escalate into saturated areas of clothing, a highly undesired effect.

Although the nylon sample doesn’t alter its airflow resistance properties, the fact that it is hydrophobic means that as soon as the individual perspires, saturated air that can not escape through the textile will remain in the microclimate and cause discomfort. In both cases, the system would benefit from a decrease in airflow resistance at higher humidity.

User trials measuring the effect of increase in textile porosity on comfort have never been conducted because a textile demonstrating this functionality is completely novel. The *Heat Index* is a tool used in weather forecasts and air conditioning industry extensively to assess how specific combinations of temperature and moisture effect physiological comfort. In order to contextualise the results in terms of physiological comfort, we will calculate the effects using the *perceived temperature*[55] tool that stems from the Heat Index.

During the Journey trials, one instance at which the individual experienced discomfort was at t_{skin} = 32^{o}C and 80%RH, the perceived temperature was much greater at 40.79^{o}C [56], according to the Heat Index, these conditions would cause great discomfort, if the relative humidity at the same temperature dropped to 70%r.h. the perceived temperature will drop to 37.99^{o}C, at 60%r.h it

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[55] Based on the Heat Index used in weather forecasting and heat/ air conditioning industries to estimate how specific combinations of temperature and humidity will make an individual feel.
[56] Used online calculation tool http://utci.nass-staufen.de/utci.php

will be 35.30^oC. The perceived temperature in the comfort zone when t_{skin}=33 and 50 % RH is 34.05. This tool highlights that small changes to microclimate moisture content cause significant reduction in perceived temperature which improves comfort sensation.

Conclusion

This chapter set out to describe the design and production process of the prototype textile. Several external and unlikely collaborators were involved in the development and testing of the prototype. The bilayer film was developed and produced in collaboration with MacDermid Autotype, a company specialising in thin films and coatings. A range of films was produced using a spin coater, from which the most suitable was reproduced using the company's pilot machine. The film was then slit using Lurex and Development facilities. Despite some technical difficulties during the processing; a useable unsupported monofilament yarn was produced. The yarn was then woven into a textile structure using traditional leno methods in the Textile Department of Chelsea College of Art and Design. Finally Dr Phil Gibson at the US Army Natick Research, Development and Engineering Centre in Natick, Massachusetts, tested the prototype.

Visual observations using the sorption analyser's controlled humidity chamber reveal that the cross section of the monofilament yarn reduces in diameter as relative humidity increases. Quantitative data provided by the test facility in Natick confirm that the structure reduces its resistance to air as the environmental relative humidity increases by 20%, suggesting that the mechanism is successful in principal. The prototype requires significant further development before the mechanism can be applied to clothing on a commercial scale. Key aspects that require further work and testing are scale, chemistry and performance. The next chapter will explore the aspects that require development and methods that might enable these technical adjustments in order to achieve a working prototype.

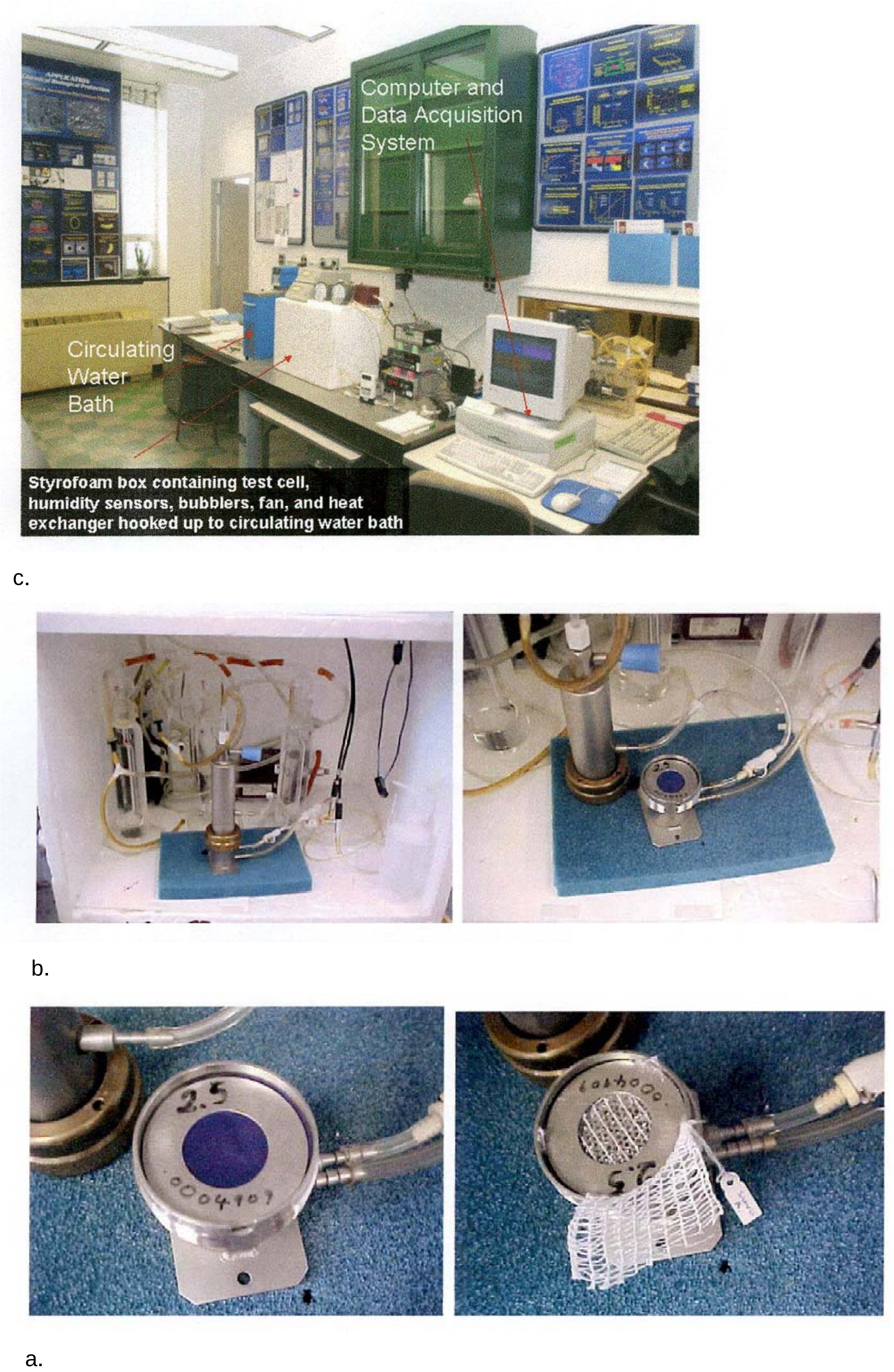


Figure 81: Photographs of testing apparatus: a. Samples in clamp, textile prototype on right, b. interior of Styrofoam box c. Apparatus layout

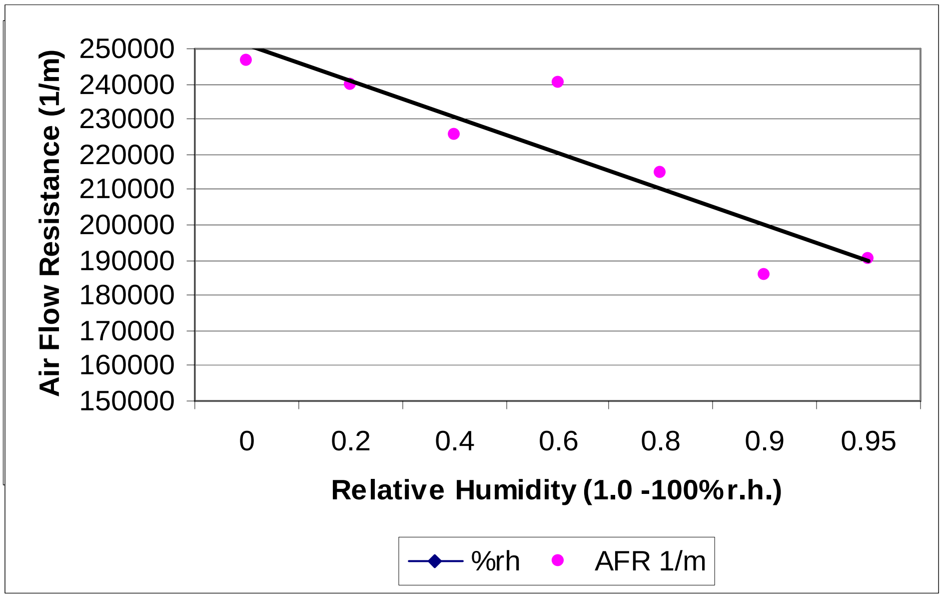
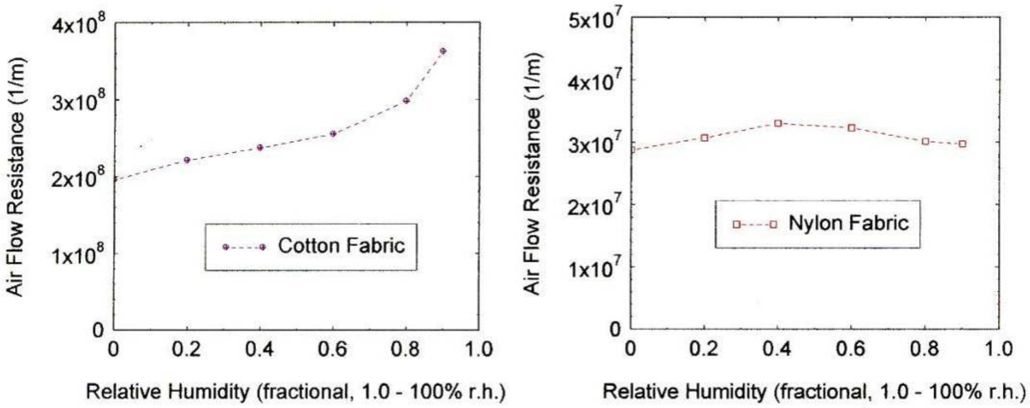


Figure 82: Prototype test results. Textile reduces resistance to airflow as humidity increases. Regression line r= -0.86



a.	b.
Cotton sample	Nylon sample
Source: Paolo Gilli	Source: William Reed
Cira: Spring/ Summer 2004	Cira: 2001
Art: Sirena	Quality: 131980
Width: 148-150 cm	Width: 155 cm
Composition: 100% Cotton	Composition: 100% Nylon 6.6
Weight: 150gr/m2	Weight: 83gr/m2
	Ends: 164/inch Picks: 98/inch

Figure 83: Results from cotton and nylon samples (source: P. Gibson, US Army Natick Soldier Systems, Natick)

Chapter 7: Future Work

Introduction

Biomimetics is a multidisciplinary field with an ever-extending reach of applications; this was evident during the development of this project. The aim of the work was to use biological examples to inspire the design of an adaptive textile that, when applied to a clothing system, would alleviate the sensation of physiological discomfort experienced by individuals travelling in an urban environment during winter. The pursuit of this aim required the achievement of several objectives described in the chapters of this thesis; the accomplishment of each step however raised more questions worthy of further investigation. This chapter will recap these objectives and reveal emerging opportunities for further work. It will also outline possible routes for the development of the existing prototype into a product suitable for application in clothing.

7.1 Project history

This project is based on previous work conducted by J. Vincent and C. Dawson in 1997 as part of the Defence Clothing and Textiles Agency (DCTA) who identified the pinecone's hygroscopic mechanism as a useful property to introduce into clothing systems that would adapt their porosity in response to changes in environmental humidity. The outcome of the research was the development of a composite textile structure whose surface imitated the functionality of the pinecone scales.

The proposed textile structure demonstrated several limitations outlined in chapter 4. In addition, from a commercial perspective, Dawson's prototype was in direct competition with breathable, water-resistant membranes that offer similar properties (Goretex, Sympatex, etc) and have a long established position in the market. The key concern is that the 'added value', adaptive behaviour conflicts with key basic requirements of clothing functionality; as the system is essentially a composite textile comprising of one knitted or woven component and one membrane, applications are restricted to external layer clothing as direct contact between skin and membrane is undesirable. The key conflict here is what happens in rainy conditions. The textile would become more porous and allow water droplets to penetrate the microclimate which is a highly undesirable effect. The version proposed by Nike (made of two layers of knitted or woven textile) also poses limitations; although it could be applied to base and mid layer clothing, any additional clothing layers would place pressure on the flaps and prevent them from working.

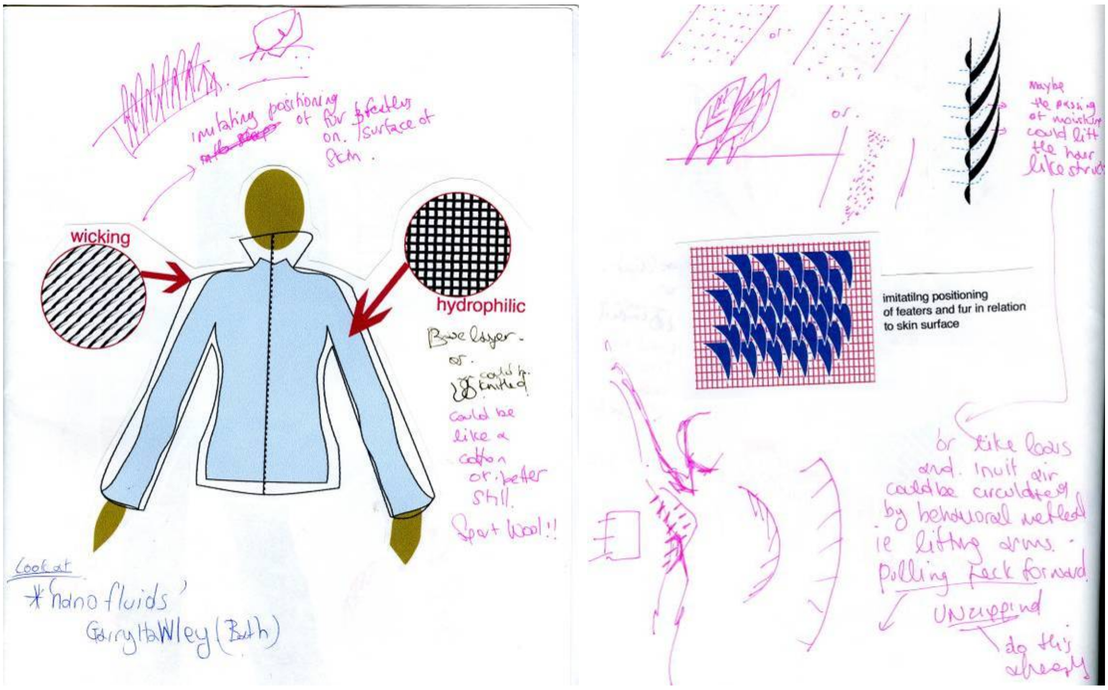


Fig 84: Initial design development. Sketches illustrate some of the thought process and design ideas for the application of Dawson (1997) prototype into clothing.

This project set out to use the mechanism identified by Dawson but develop a more suitable interpretation for the textile and clothing sector; figure 84 illustrates some of the original design ideas using both the ‘pinecone effect’ textile prototype and concepts from the arctic fur and penguin feathers. These textile systems were designed for application onto external and single layered clothing and could be realised using a variety of techniques i.e. synthetic fur construction using active fibres in the pile components.

7.2 Research overview

Consumers are exposed to smart and adaptive technologies through the products that they purchase. Chapter 1 identified that new functionalities introduced into clothing systems mainly target psychological applications, while there are significant opportunities in addressing the physiological needs of individuals especially in common situations encountered during urban travel where an individual passes through a multitude of environments with different conditions (temperature, humidity).

Commercially available ‘adaptive’ textile products employ temperature as an activation stimulus either for latent heat storage or in film form (able to alter their permeability to moisture according to the environmental temperature). Both microcapsule and membrane mechanisms are limited; PCM performance is analogous to the quantity of product in the fibre or foam and has a finite capacity for heat storage and release. Smart membranes respond to external temperature, thus the mechanism does not respond to the needs of the user and is influenced by external factors independent of the wearer’s comfort levels.

The product review highlighted questions regarding the relationship between microclimate temperature and sensation in the context of physiological comfort or discomfort. Although many products employ temperature as a trigger for adaptive behaviour, and claim that this is the best option in their marketing literature, the lack of evidence raises questions on suitability. Furthermore, there have been very few studies designed to isolate the microclimate factors effecting comfort sensation. It was therefore necessary to design and execute a series of experimental trials to help answer these questions.

The Journey trials (chapter 2) employ aspects of the methodology used by Li (2005) with adaptations to suit a non-lab based environment. The findings suggest that that microclimate skin temperature alone is not a satisfactory objective parameter and would not function successfully as a trigger for an adaptive clothing system. Microclimate moisture concentration coupled with temperature however appears to be directly linked to perceived comfort. The data also produced an experimental model (comfort zone) that provides an illustration of the parameters of comfort sensation in terms of microclimate %RH and temperature.

There are several examples in the botanical world where environmental moisture is used to manage seed/ spore dispersal. These mechanisms demonstrate a range of movements based on one of two principles: cohesion or imbibition, discussed in chapter 3. The latter was identified as the most suitable for technology transfer because the phenomenon is also present in conventional textile fibres although not utilised as in the plant world. The shrinking/ swelling properties of fibres is in fact mostly considered a problem in the textile industry and rarely used as a ‘tool’.

The imbibition principle is realised in botanical structures through the manipulation of the orientation of cellulose microfibrils that comprise the cell walls of a particular plant structure. Opposing forces are created in adjoining areas of cell whose cellulose orientation differs; in general terms, during sorption the closer the microfibril angle is to the axis of the particular organ the less dimensional swelling is exhibited.

Although the orientation of polymer chains in man-made fibres can be controlled through stretching during extrusion, it is not yet possible to manipulate the orientation as precisely as in the natural paradigms studied in chapter 3. Hygroscopic bending or curling motion has been simulated in the man-made fibre sector by engineering bicomponent fibres from polymers with different swelling properties. These moisture sensitive fibres increase their crimp when dry and straitening out when wet. Although this is promising neither corporations that pioneered this technology have identified a successful method of embedding the functionality of the fibres into a textile system (chapter 4).

Tang & Stylios (2006) found that textile constraints such as structure and finish can affect shape recovery in SMP fibre applications and the overall effect is reduced when active fibres are blended with conventional fibres. In the case of the moisture sensitive fibres, the filaments are applied directly into yarns and blended with non-active fibres then woven or knitted into textile structures. Due to the nature of the active fibre shape change properties, the yarns contract in length when dry and elongate when wet thus creating unstable structures (see chapter 4).

Attempts to create a moisture sensitive textile have been realised using mechanisms that function at the top of the textile structure hierarchy (‘pinecone effect’) and at the very bottom (moisture sensitive fibres), both applications are promising but present key limitations. This project proposes a solution that places the mechanism into a yarn structure that appears to have overcome the limitations presented by other competing technology.

7.3 Further investigation

7.3.1 Impact of textile innovation

Physiological comfort is a relatively new concept to the clothing sector whose importance was recognised as a result of the negative sensations experienced by consumers of garments made from synthetic fibres in the 1970’s. Numerous studies conducted on textile structure and human sensation in relation to comfort have shed much light on key factors that influence physiological discomfort.

The literature review in chapter 1 revealed that between the work of the dress reformist and 1970’s; over a century had passed with little historical reference to comfort from clothing and how this was influenced by technological innovation. The psychological aspects of comfort in western dress have been well documented indirectly by dress historians, as has the social impact of mass-produced synthetic fashion products. However, there appears to be little work conducted on the transition of ‘comfort from clothing’ in Victorian times to that of the modern era and how the pressures from technological innovation and lifestyle have affected consumer expectations.

A more thorough historical study of the effects of technological innovation on the functional profile of clothing and the changes to consumer lifestyle would be of great interest. A good starting point would be the study of clothing properties from other cultures, whose dress has been subjected to minor structural alterations over the centuries such as the Inuit costume, kimonos and saris. Such a study is timely and of significant importance today due to the increasing volume of technology imports from medical and other sectors into clothing. As the prediction and management of potential commercial outcomes becomes increasingly necessary, it would be of great value to understand how past developments have effected consumers.

7.3.2 Journey trials and the comfort zone

The current trend in ‘smart’ textiles that manage physiological comfort is to respond to changes in temperature. The suitability of this particular stimulus was challenged using experimental trials that drew upon lab-based methods and applied them to non-lab conditions. Although the findings suggested that in the context of travel within an urban environment, microclimate moisture content is a more representative factor of wearer comfort, the fact that they were conducted on a single subject means that the results are indicative and not conclusive. The journey trials are unique as there is no other work that has been conducted in ‘real’ conditions and looked for parameters of comfort sensation in order to identify a threshold, but further work is necessary to draw satisfactory conclusions.

The Journey trials and comfort zone study can be regarded as a pilot or a model for a larger scale project. The trials were conducted on a single subject, opinions are divided on whether n=1 is an adequate sample range and that possibly n=6 should be used in the study. Given the time scale and available resources, n=1 was deemed suitable for the purposes of the project as the aim of this work is to develop a prototype and not perfect a new testing method. The exercise did raise many questions that are certainly worthy of further pursuit.

Aspects of the work have already been used as a foundation for a series of experiments conducted by the Wool Service Desk at the Western Australian Department of Agriculture. The research group headed by John Stanton[57] are conducting a series of experiments based on the methods outlined in chapter two with a view to evaluate and improve the quality and performance of the region's wool based products and technology. The department has invested in a climatic chamber and trials are being conducted on 40 individuals, initial objectives are to study the effect of relative humidity on changes in skin temperature and comfort sensation.

Although the general consensus in the textile industry suggests that all human beings respond in a uniform manor to such stimuli, which is supported by findings of experimental work using psychophysical methods, it would be ideal to verify this on a larger sample and explore factors such as gender, ethnic origin and physical ability and compare results. As mentioned in chapter 2 physiological conditions such as menopause and Asperger syndrome can create variations in individual response. These cases are certainly worth further exploration.

7.3.3 Biomimetics

The biomimetic analysis in chapter 3 was unique from the perspective of a biological study, as the range of botanical samples subjected to sorption analysis had not been previously conducted. Various types of wood had been

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[57] John Stanton, Senior Research Officer, Wool Service Desk, Department of Agriculture, 3 Barron Hay Court South Perth, Perth, Western Australia 6151

previously studied and Dawson isolated and analysed the two types of tissue responsible for the opening and closing mechanism of the pinecone. Although pine cones, legume valves, geranium seed pods etc function using the imbibition principle, the scale at which this is actuated varies greatly between the pinecone and the rest of the samples.

Although it was possible to separate the two tissue types in the pinecone, differences in microfibril orientation have evolved within single cells of the other specimen and thus were impossible to separate with the available skills and resources. Given the findings of Dawson (1997) the study of the different cell parts may have been pointless as the volume of moisture ad- and desorbed were identical in the case of the pinecone. Further study would be necessary to verify this though.

Instead, the mechanism as a whole was subjected to sorption analysis but the nature of the study was observational to help extract a general principle it also confirmed the findings of the literature review. Although some observations were made in terms of the way moisture interacts with fibres, it would be worthwhile to use sorption analysis methods to further study the imbibition mechanism from a structural perspective. Ideally by a biologist or an individual skilled enough to optimise the information gained from the data and reveal in greater detail the way in which moisture interacts with the substrate at various humidities and the effects of structural parameters particular to each species.

7.3.4 Adaptive textile prototype

The aim of this work was to design, construct and evaluate a textile structure that would be suitable for application in a clothing system and would adapt its permeability to air in response to the moisture content of the system’s microclimate. Experimental trials suggest that the structure should begin to increase its permeability when the relative humidity in the microclimate reaches 50% and increase resistance below 45% RH.

The outcome of this work is a textile prototype that does demonstrate a reduction in resistance to the passage of air in increased humidity. The structure's adaptive mechanism was inspired by botanical structures that use imbibition principals to actuate seed dispersal and the technology transfer was enabled using limited resources. As described in chapter 6, a bilayer film was created and slit into monofilament yarns that were woven into a leno based textile structure. Laboratory based testing in specialist military research facility revealed that the textile sample demonstrated average air resistance of 2.3 X 10^5 / m up to 60% RH and dropped to an average of 1.9 X 10^5 / m from 70-95% RH. Although the scale, performance and chemistry were far from ideal, the prototype was adequate to suggest the mechanism is successful.

The adaptive textile has several advantages over the original pinecone fabric: the functionality is not visual and although the sample tested demonstrated that the mechanism does not operate under the stresses of the clamping system, it is not limited to single layer and localised applications, the dimensions of the sample are also unaffected by actuation. In its current form the prototype is not suitable for application in clothing and further work is required. The project has received significant commercial attention and pressures from industry suggest that further development is worthwhile.

One key area that requires development is the chemistry of the bilayer structure. The film used in the prototype is made from two layers of water-soluble cellulose materials, this was a necessary compromise enforced by time and resource restrictions. As a result the film is easily damaged in higher humidity and totally inappropriate for use in actual clothing. A non-soluble combination needs to be identified and ideally would involve chemicals already used in the textile industry. The patent review in chapter 4 disclosed two existing combinations of chemicals; one used modified polyethylene terephthalate and polyalkeylene glycol-containing nylon while the other used two types of cellulose acetate with different sorption properties. The acetate combination appears to be more reliable and better performance and would therefore be an ideal starting point for the development of the chemistry.

The prototype used 0.8 mm of unsupported monofilaments that had been sliced using a conventional method of producing decorative metallic fibres and yarns. Although this was adequate for the production of a sample suitable for testing, further development is necessary to reduce the scale of the fibre or yarn so it can be incorporated into a clothing system. The slit film method is an easy and effective way of producing a yarn, but is not the ideal for use in textiles for clothing as the scale limits application possibilities. Like the sample produced, the textile structure would have to be very open; it is therefore ideal that the next stage of development focuses on the production of a bicomponent fibre.

Finally further testing would be required to asses the performance of the various outcomes and the effect of structural parameters such as yarn and textile structure, this could be done by Phil Gibson at Natick. It would also be necessary at this stage to assess the effect of changes in air permeability on physiological comfort. So far, based on existing literature it has been assumed that this would prevent or postpone discomfort sensations, but there have been no trials to verify this. It would be necessary to design another phase of user trials possibly based on the Journey model to evaluate the effectiveness of such an adaptive structure.

Conclusion

This chapter has examined the achievements of the overall project both in terms of the creation of a textile prototype and all the preliminary work that has gone into the design and development of the concept. As a result opportunities for further work in the fields of dress history, botany and clothing science have been identified. The developmental work reached as far as the production of a prototype that offers proof that the performance of the proposed mechanism is successful but in need of further work if the concept is to be applied in the commercial sector.

The following applications have been identified from various areas of the textile industry:

- **Athletic wear:** active sportswear
- **Performance wear:** climbing, walking, skiing
- **Comfort wear**: underwear, nightwear
- **Military:** underwear, multi-climate clothing
- **Health:** hospital bed linens, wound dressings
- **Agricultural technology:** Geo-textiles, greenhouse screening panels, soil moisture control
- **Technical solutions:** F1, firefighting, industrial clothing
- **Industrial:** filter & valve technology, building, packaging
- **Upholstery:** transport, domestic

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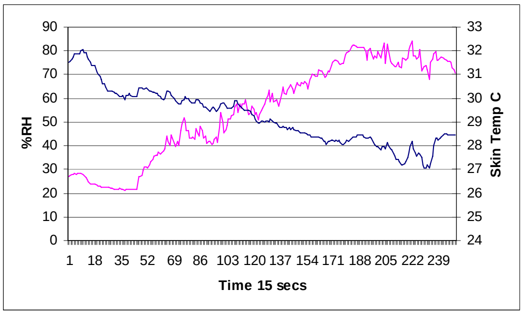
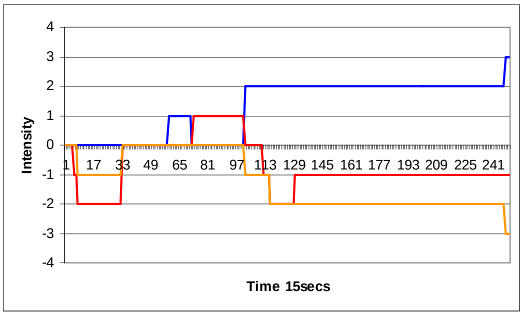
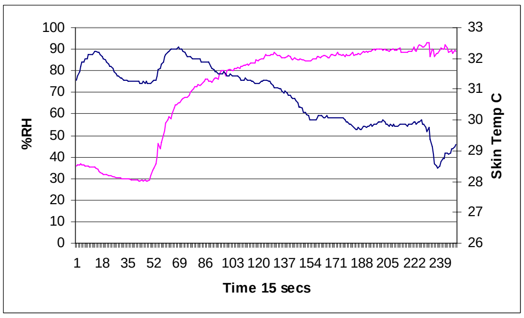
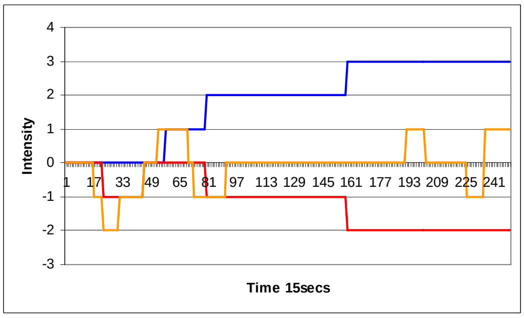
Appendix 1: Journey trial graphs

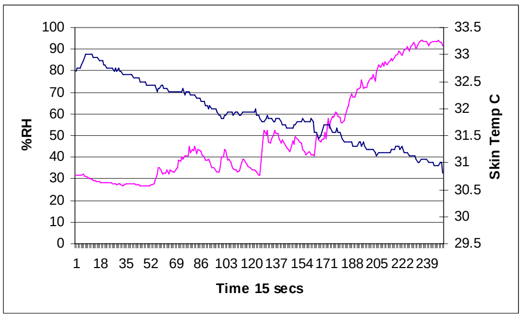
Objective and Subjective Trial Data

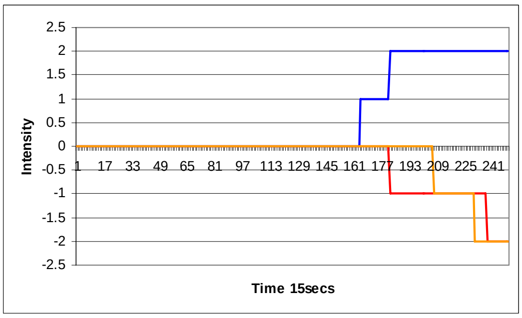


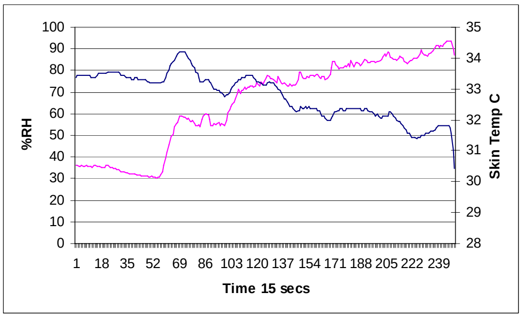


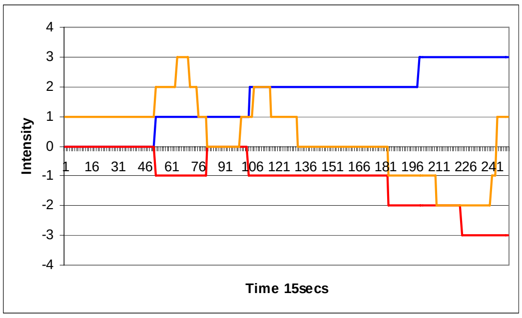


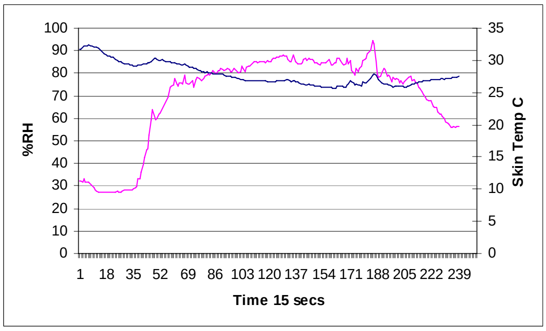


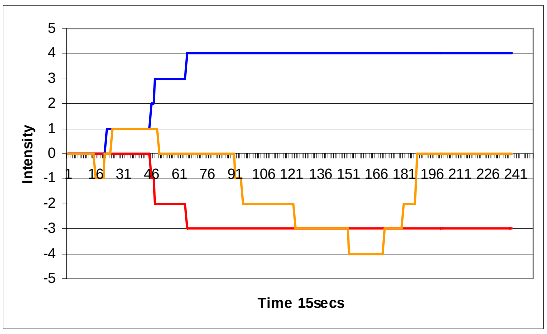








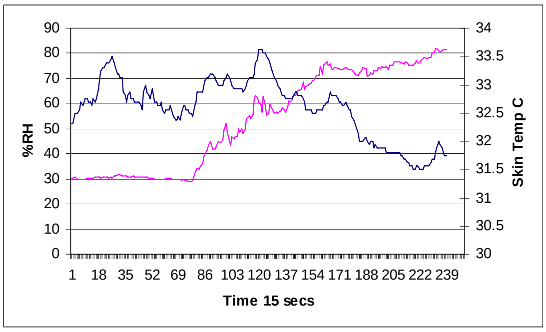


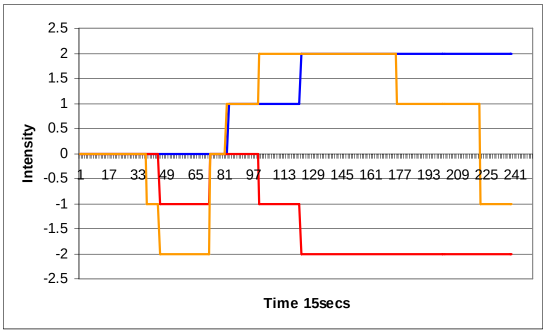


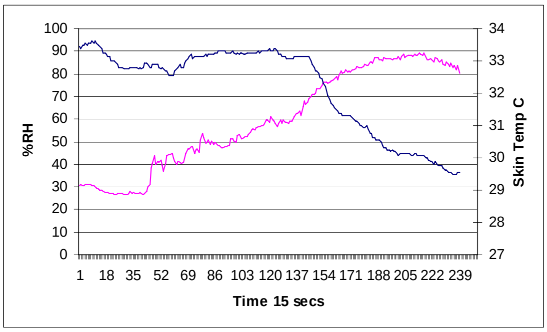
Key:

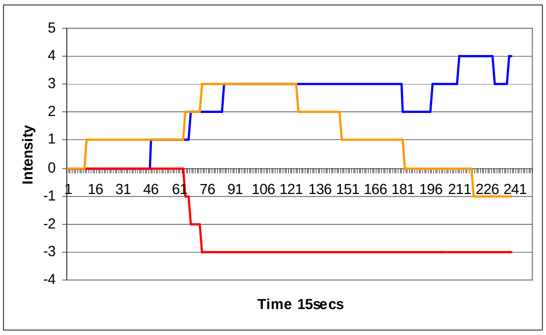
Skin Temperature ▬ Sensations:

Relative Humidity ▬ Moisture ▬ Thermal ▬ Comfort ▬







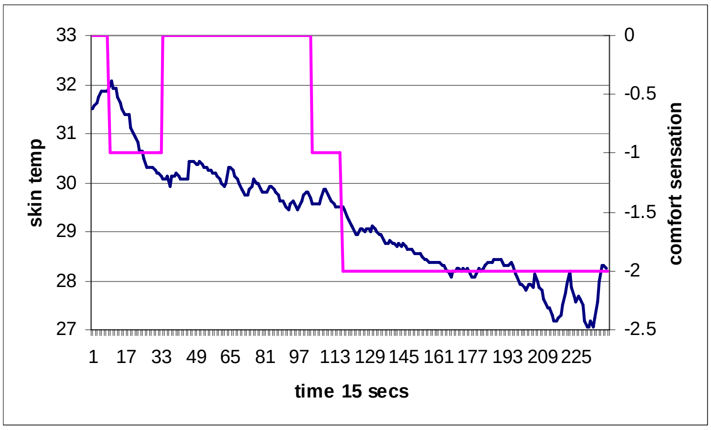


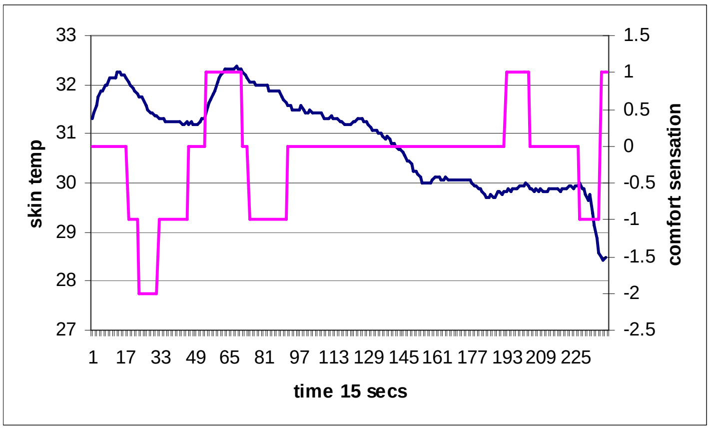
Key:

Skin Temperature ▬ Sensations:

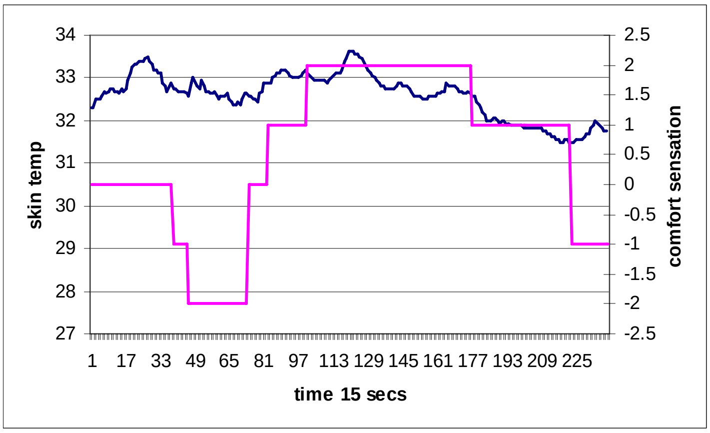
Relative Humidity ▬ Moisture ▬ Thermal ▬ Comfort ▬

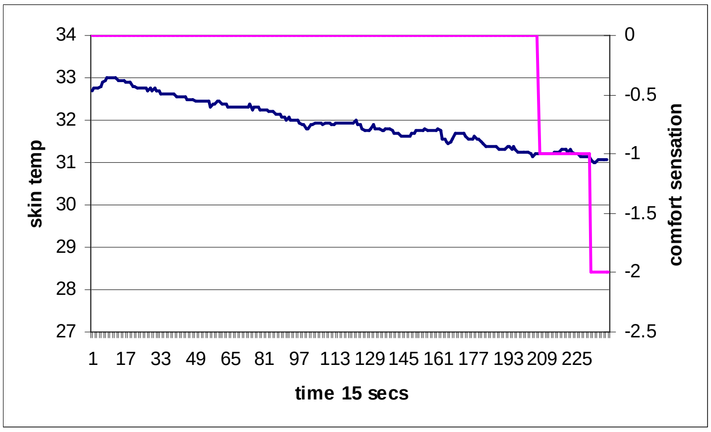
Comfort and skin temperature

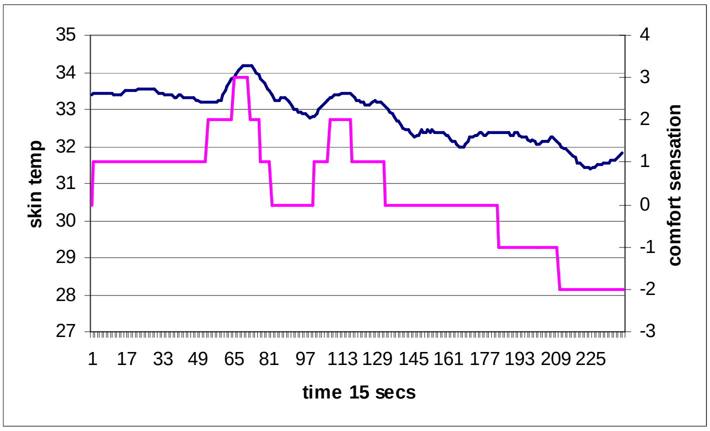


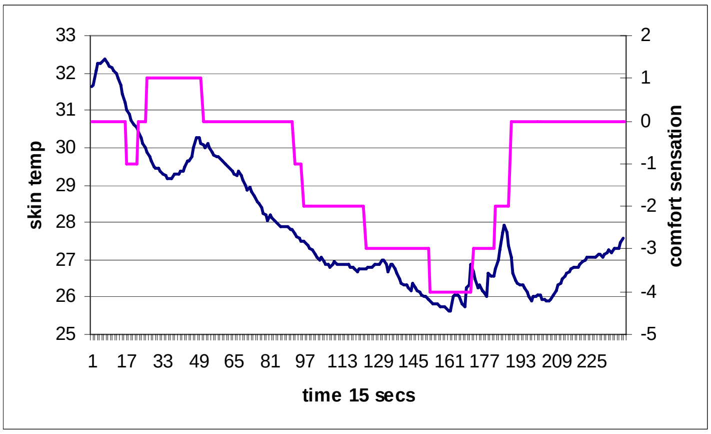


Key: Comfort ▬ Skin temperature ▬

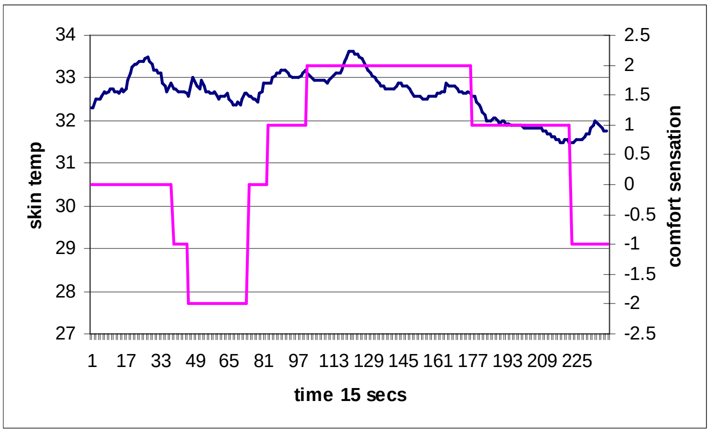


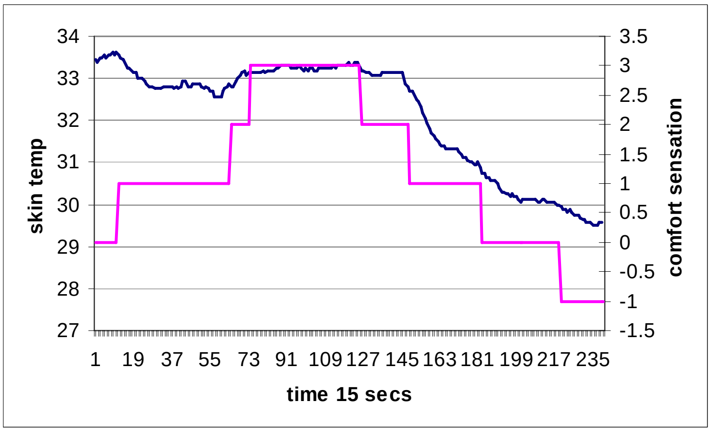






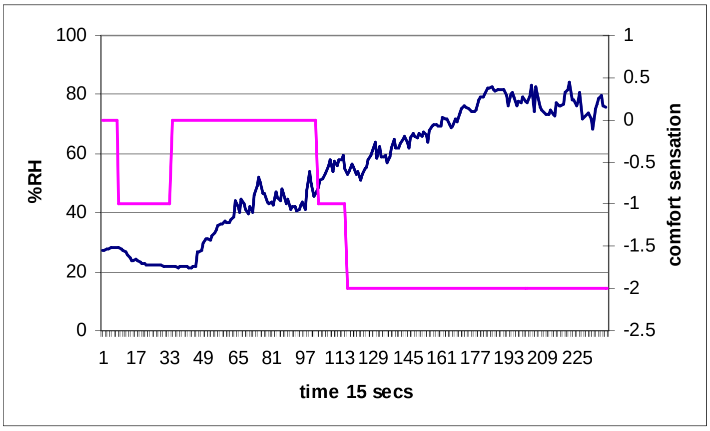
Key: Comfort ▬ Skin temperature ▬



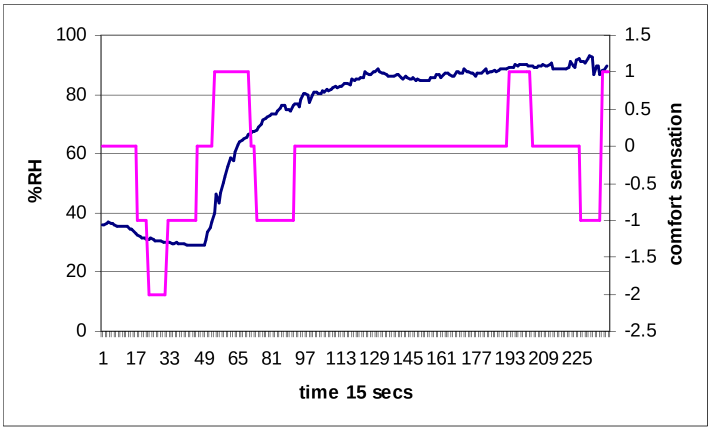


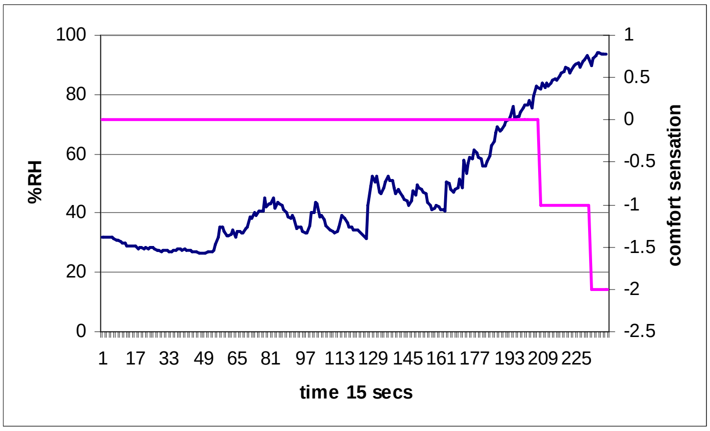
Key: Comfort ▬ Skin temperature ▬

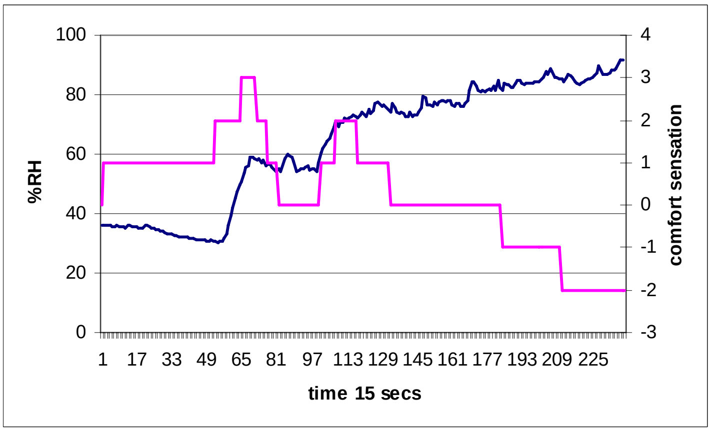
Comfort and relative humidity

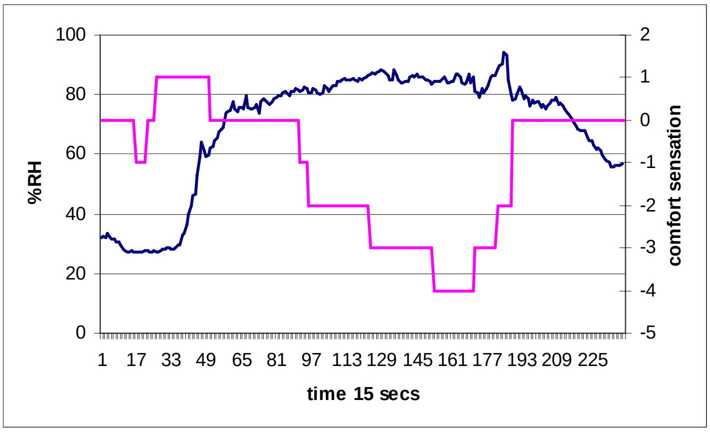


Key: Comfort ▬ Relative Humidity ▬

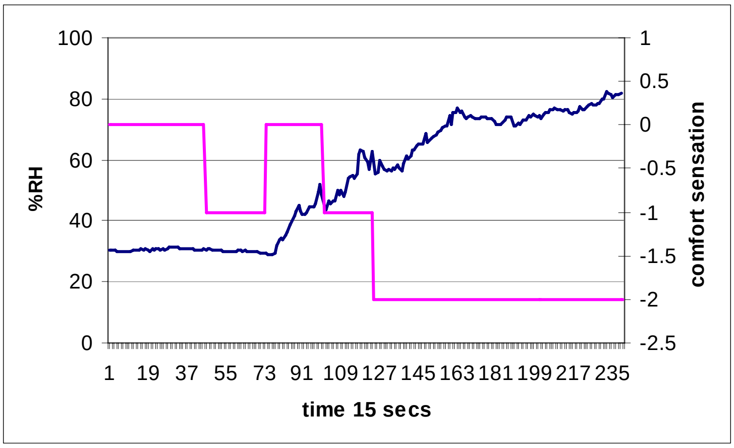


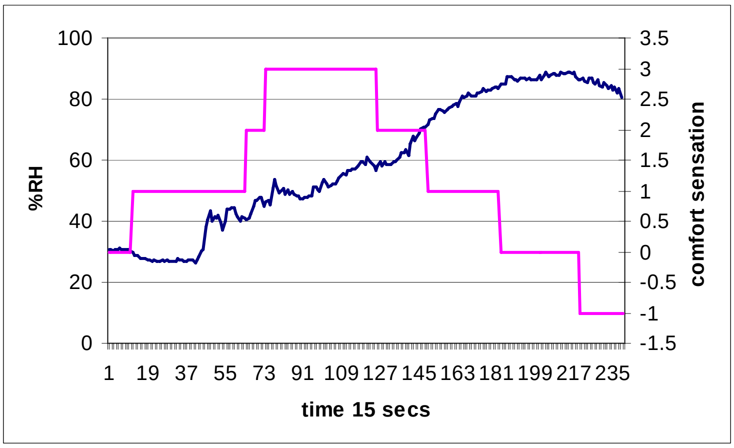






Key: Comfort ▬ Relative Humidity ▬





Key: Comfort ▬ Relative Humidity ▬

Appendix 2: List of Cisorp experiments

Botanical

Test Name	Comments
BT01	2X equisetum spores Try run test 4 24 hours
BT02	2X equisetum spores Long test run, results identical to bt01
BT03	2X equisetum spores on new database 60min min run time 18hrs long other sample, need to make 80 & 90 %RH a longer step!
BT04	2X Geranium weight jumped a bit on one sample so will try using heavier samples this time
BT05	2X Geranium used 3 specimens in each dish to increase the weight and hope for better results, both samples had similar behaviour this time. Need to keep this in mind
BT06	2X Geranium
BT07	2X Legume black
BT08	2X Legume black
BT09	2X Legume black
BT10	2X Legume Large Not equilibrating, need to increase step times maybe will monitor next results
BT11	2X Legume Large
BT12	2X Legume Large
BT13	2X Legume small
BT14	2X Legume small
BT15	2X Legume small

Cellulose Fibres

Test Name	Comments
Fib16	2X California Cotton Untreated
Fib17	2X California Cotton Untreated
Fib18	2X California Cotton Treated High weight gain over 50%
Fib19	2X California Cotton Treated Balance a very high weight gain over 150%
Fib20	2X Mid South Cotton Untreated
Fib21	2X Mid South Cotton Untreated
Fib22	2X Mid South Cotton Treated
Fib23	2X Mid South Cotton Treated
Fib24	2X Easter Cotton Untreated
Fib25	2X Easter Cotton Untreated
Fib26	2X Easter Cotton Treated
Fib33	2X Lenzing Viscose 1,7dtex
Fib37	2X Lenzing Viscose 1,7dtex

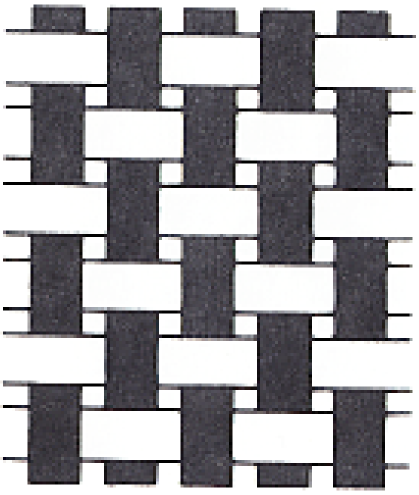
Appendix 3: Cisorp paper and fibre experiments

Test Name	Test Date	K	I	Comments
Test 20	05/09/06	Y	Y	P=1.8 I=2.5 D=0.002 A=3 min water seal CO B = untreated CO 4 cycles
Test 21	06/09/06	Y	Y	A= 2 min 5mol NaOH CO B= untreated CO cut at 16 steps; treatment not improving sorption
Test 22	06/09/06	Y	Y	A= 6 mins 5mol NaOH CO B= untreated CO 21 steps; no improvement in sorption/ will try wetting cotton
Test 23	06/09/06	Y	Y	A= 30 sec 5mol Urea VI B= untreated VI 4 cycles no equilibrium
Test 24	07/09/06	Y	Y	A=30 sec 5mol Urea VI B= untreated VI ? cycles made minimum no change time 30 mins then changed it to 45
Test 25	07/09/06	Y	Y	A= 3 min Water Seal VI B= untreated VI 2 cycles with 60 mins, min step time at 90 RH the step ran for hours
Test 26	12/09/06	Y	Y	A= 3 min Water Seal VI B= untreated VI 1 cycles with 60 mins, min step time same behaviour at 90 RH step, stopped it manually. Wonder why it does that?!
Test 27	12/09/06	Y	Y	A= 6 mins 5mol NaOH CO b= washed untreated CO 2 cycles 30 min minimum step time
Test 28	13/09/06	Y	Y	A= 1min 5mol Urea CO b= washed untreated CO 30 min step time 1 cycle
Test 29	13/09/06	Y	Y	A= 30 sec 5mol Urea VI B= washed untreated VI 1 cycle; the kinetic graph looks weird because the steps are a bit mixed up. Exported file from Access database so there is a chance it messed up a bit.
Test 30	25/09/06	Y	Y	A= 90 sec 5mol Urea paper tape B= untreated paper tape; results bit messy (possibly because the machine was switched off and ken had to change the database) but the treatment seems to reduce mass absorption? Weird it is the opposite effect it has on cotton cellulose!
Test 31	26/09/06	Y	Y	A= 90 sec 5mol Urea treated paper tape B= washed untreated paper tape cut samples this time same results but tidie
Test 32	26/09/06	Y	Y	A=90 sec 5mol NaOH treated paper tape B= washed untreated paper tape 3 pieces of sample each, I suspect that the points don't join or are at greater distance apart than they possibly could be at around 50RH because
Test 33	27/09/06	Y	Y	A =2 h waterseal treated paper tape B = washed untreated paper tape
Test 34	27/09/06	Y	Y	A= 6 min 5mol NaOH treated paper tape B= washed untreated paper tape
Test 35	02/10/06	Y	Y	A= 6min 5mol Urea VI B= washed untreated VI
Test 36	02/10/06	Y	Y	A= 6min 5mol Urea CO B= washed untreated CO
Test 37	03/10/06	Y	Y	A=6min 8 mol Urea Paper tape dH_20 B= 6min 8 mol paper tape dH_20 then tap washed
Test 38	03/10/06	Y	Y	A=2min 8 mol Urea VI dH_20 B= 2min 8 mol Urea VI dH_20 then tap washed
Test 39	04/10/06	Y	Y	A=6min 8 mol Urea CO dH_20 B= 6min 8 mol CO dH_20 then tap washed
Test 40	04/10/06	Y	Y	A=6min 8 mol Urea CO dH_20 B= CO untreated tap washed
Test 41	10/10/06	Y	Y	A=6min 8 mol Urea Paper Tape dH_20 B= Paper tape untreated tap washed
Test 42	10/10/06	Y	Y	A=2min 8 mol Urea VI dH_20 B= untreated VI tap wash
Test 43	11/10/06	Y	Y	A= unwashed VI B= tap water VI

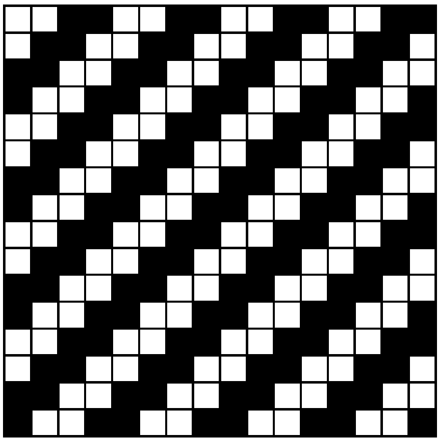
Test 44	11/10/06	Y	Y	A= unwashed CO B= tap water CO
Test 45	16/10/06	Y	Y	A= 6min 5mol NaOH CO B= washed untreated CO; results similar for both samples so running another test
Test 46	17/10/06	Y	Y	A= 6min 5mol NaOH CO B= washed untreated CO
Test 47	17/10/06	Y	Y	A= 6min 5mol NaOH CO B= washed untreated CO same samples as 46
Test 48	18/10/06	Y	Y	A= 6min 5mol NaOH CO B= washed untreated CO new samples
Test 49	30/10/06	Y	Y	A= untreated nettle paper B= untreated manila paper tape
Test 50	31/10/06	Y	Y	A= untreated nettle paper B= untreated manila paper tape
Test 51	31/10/06	Y	Y	A=3 min water seal CO B = untreated CO
Test 52	1/11/06	Y	Y	A=2min 8 mol Urea VI dH_20 B= untreated VI tap wash
Test 53	1/11/06	Y	Y	A=6min 8 mol Urea CO B= CO untreated tap washed results were similar
Test 54	6/11/06	Y	Y	A=6min 8 mol Urea CO B= CO untreated tap washed different samples this is really odd, the treated cotton still is not performing as it did in test 39 and 40, I think it may have something to do with the tap water ?
Test 55	7/11/06	Y	Y	A= untreated nettle paper B= untreated manila paper tape
Test 56	7/11/06	Y	Y	A=6min 8 mol Urea CO dH_20 B= CO untreated tap washed Very strange, still similar even though I used the one washed in distilled water
Test 57	8/11/06			A=2min 8 mol Urea VI dH_20 B= untreated VI tap wash

Appendix 4: Weave structures

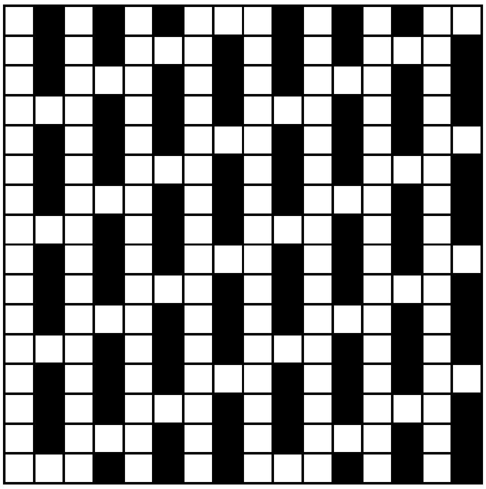
Plain weave: Each weft yarn crosses the warp yarn by going over one, then under the next, and so on.



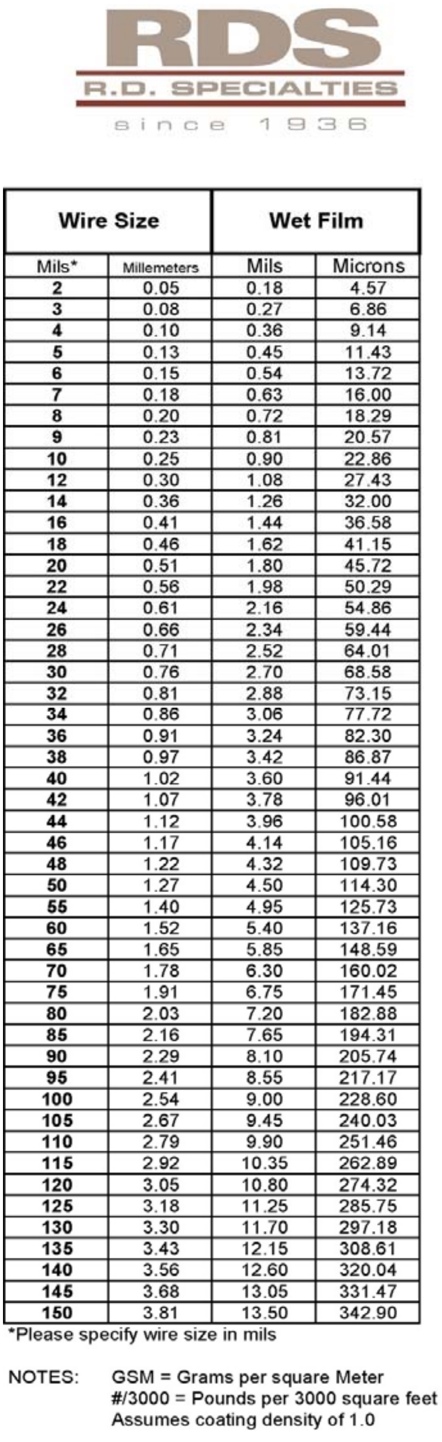
Twill weave: each weft yarn floats across two or more warp yarns in a progression of interlacings by one to the right or left, forming a distinct diagonal line. This diagonal line is also known as a wale. A float is the portion of a yarn that crosses over two or more yarns from the opposite direction.



The satin weave is characterized by four or more cool fill or weft yarns floating over a warp yarn or vice versa, four warp yarns floating over a single weft yarn. This explains the even sheen, as unlike in other weaves, the light reflecting is not scattered as much by the fibres, which have fewer tucks.



Appendix 5: Meyer Rod specification



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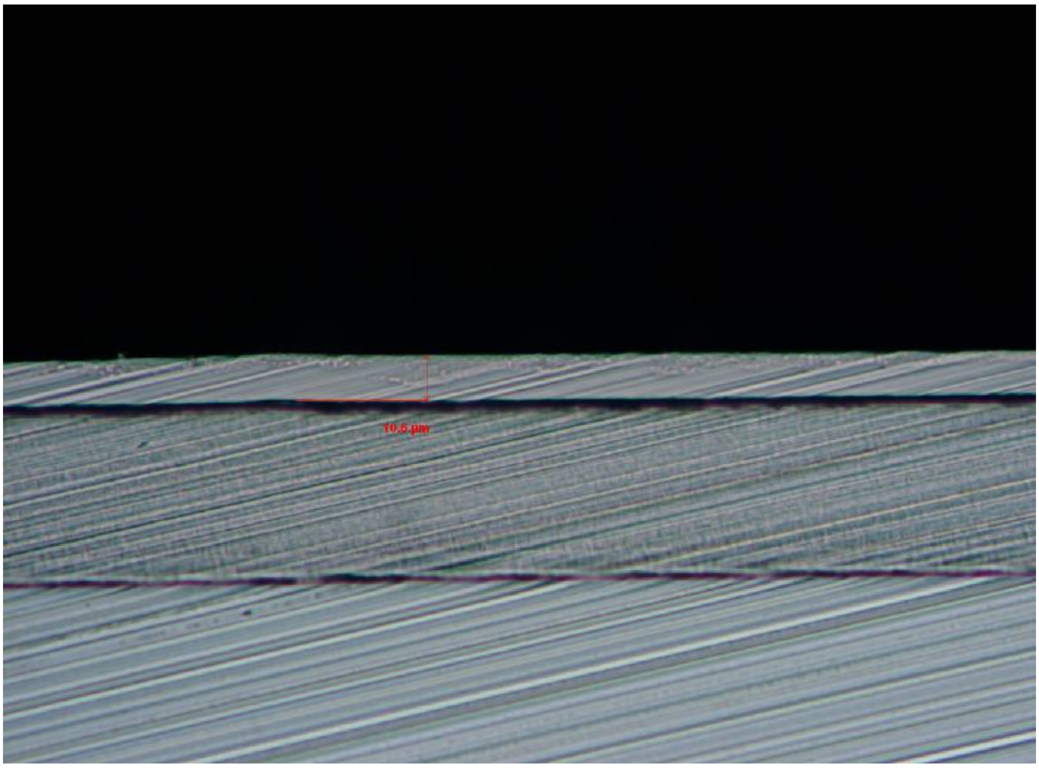
Wire Size		Wet Film	
Mils*	Millemeters	Mils	Microns
2	0.05	0.18	4.57
3	0.08	0.27	6.86
4	0.10	0.36	9.14
5	0.13	0.45	11.43
6	0.15	0.54	13.72
7	0.18	0.63	16.00
8	0.20	0.72	18.29
9	0.23	0.81	20.57
10	0.25	0.90	22.86
12	0.30	1.08	27.43
14	0.36	1.26	32.00
16	0.41	1.44	36.58
18	0.46	1.62	41.15
20	0.51	1.80	45.72
22	0.56	1.98	50.29
24	0.61	2.16	54.86
26	0.66	2.34	59.44
28	0.71	2.52	64.01
30	0.76	2.70	68.58
32	0.81	2.88	73.15
34	0.86	3.06	77.72
36	0.91	3.24	82.30
38	0.97	3.42	86.87
40	1.02	3.60	91.44
42	1.07	3.78	96.01
44	1.12	3.96	100.58
46	1.17	4.14	105.16
48	1.22	4.32	109.73
50	1.27	4.50	114.30
55	1.40	4.95	125.73
60	1.52	5.40	137.16
65	1.65	5.85	148.59
70	1.78	6.30	160.02
75	1.91	6.75	171.45
80	2.03	7.20	182.88
85	2.16	7.65	194.31
90	2.29	8.10	205.74
95	2.41	8.55	217.17
100	2.54	9.00	228.60
105	2.67	9.45	240.03
110	2.79	9.90	251.46
115	2.92	10.35	262.89
120	3.05	10.80	274.32
125	3.18	11.25	285.75
130	3.30	11.70	297.18
135	3.43	12.15	308.61
140	3.56	12.60	320.04
145	3.68	13.05	331.47
150	3.81	13.50	342.90

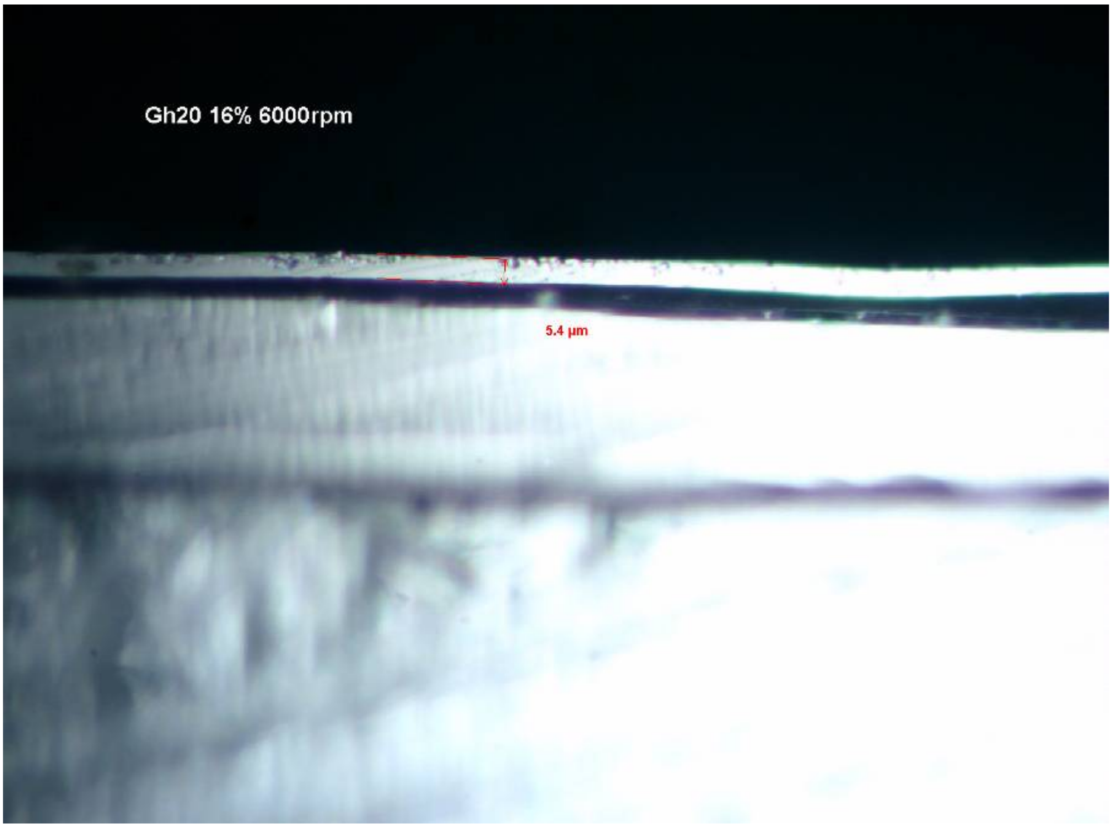
*Please specify wire size in mils

NOTES:
GSM = Grams per square Meter
#/3000 = Pounds per 3000 square feet
Assumes coating density of 1.0

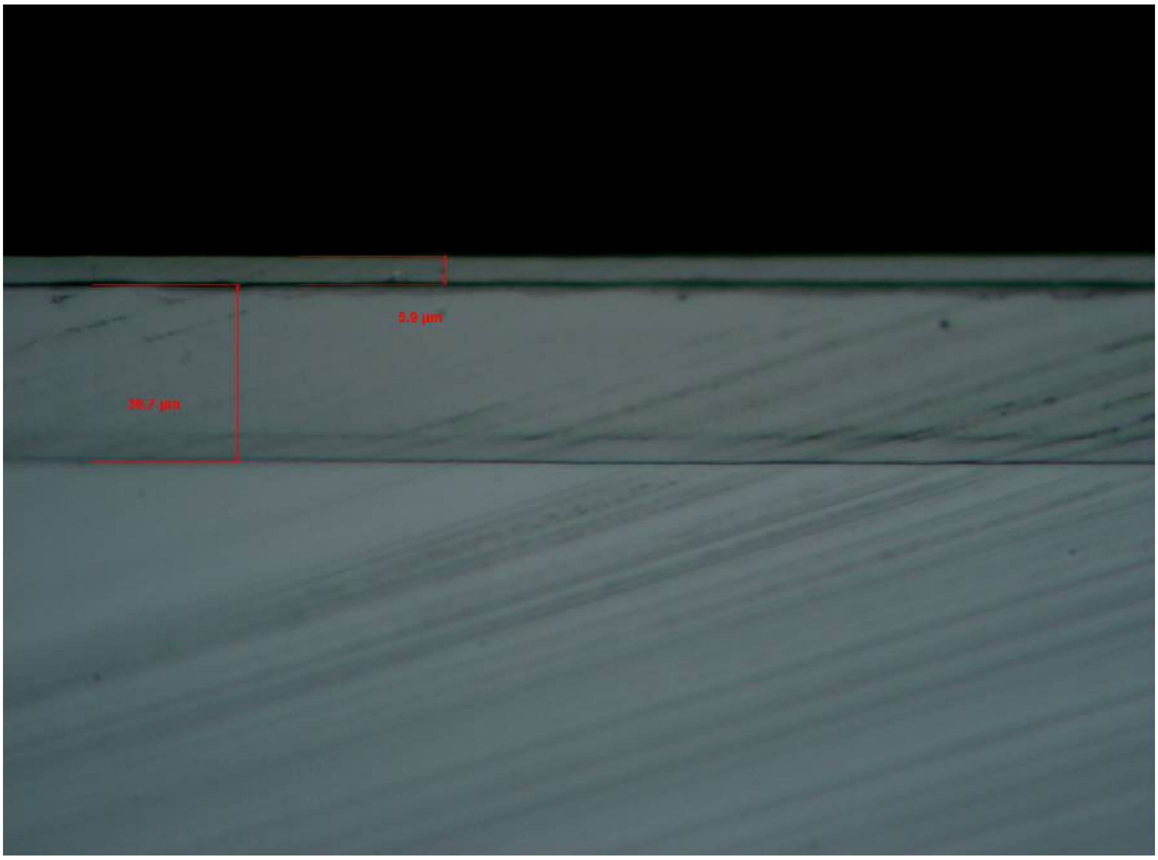
Appendix 6: Film thickness images



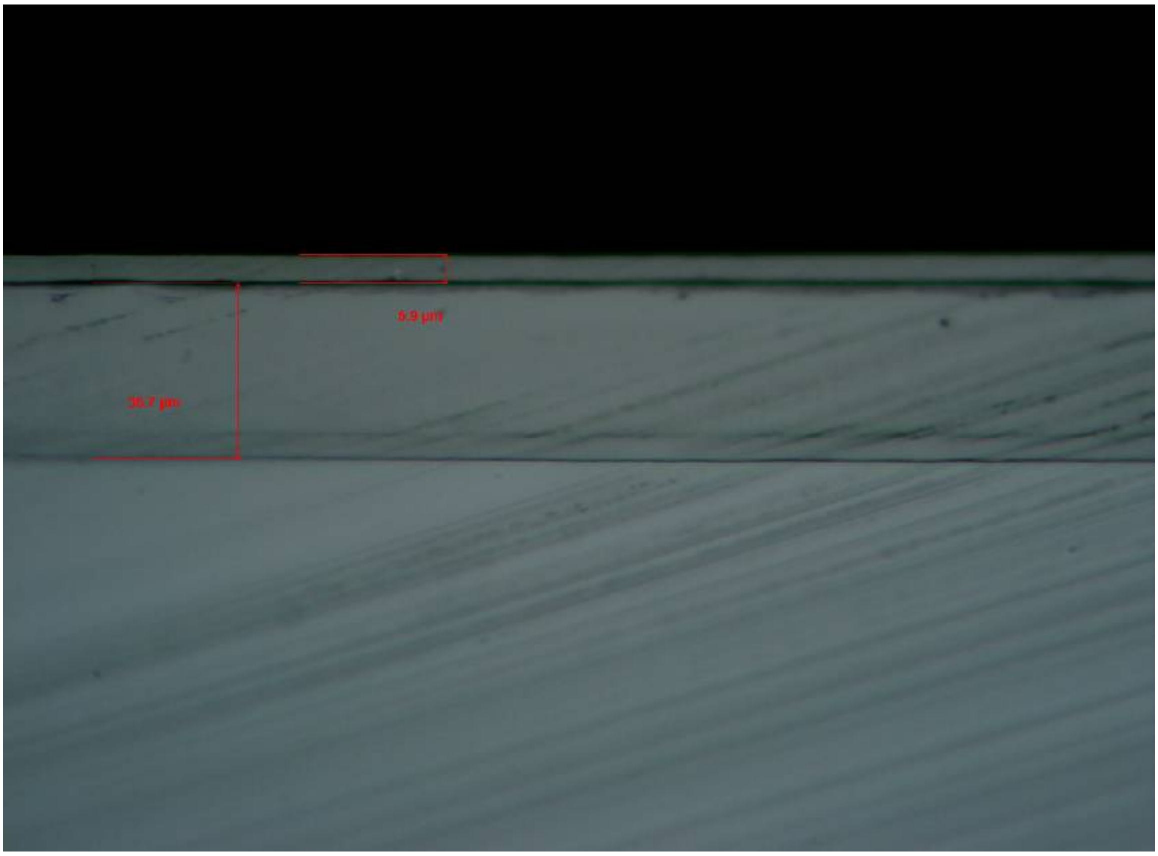
GH20 16% at 3000 rpm



GH20 16% at 6000 rpm

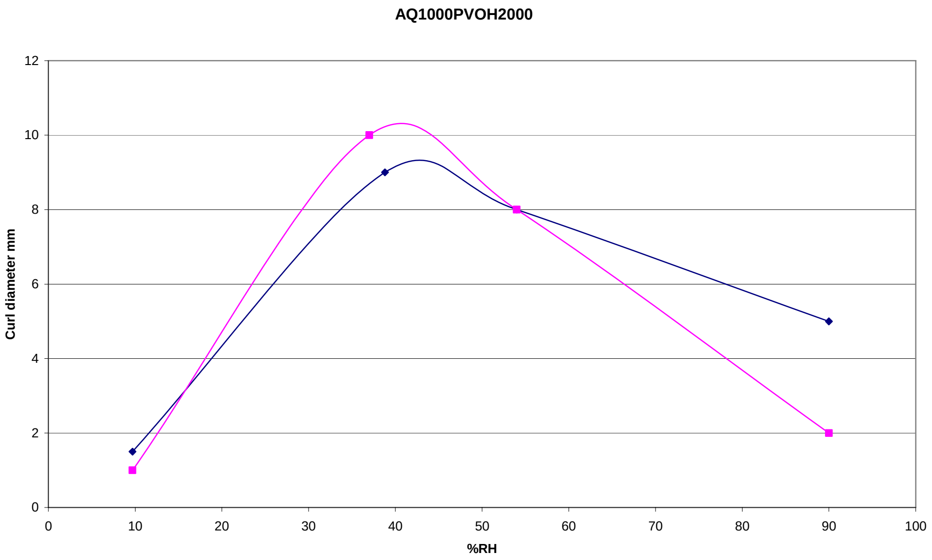


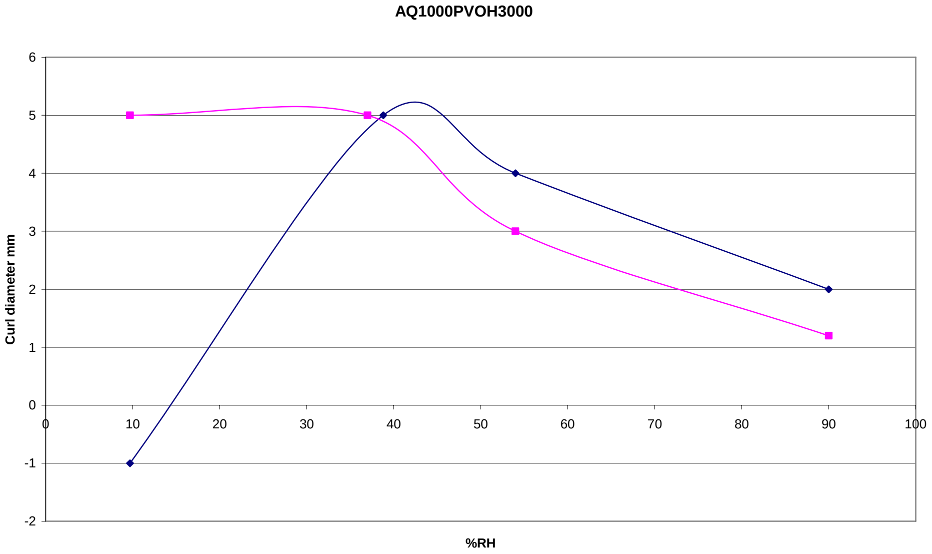
Aqualon N200 6.5% at 1000 rpm

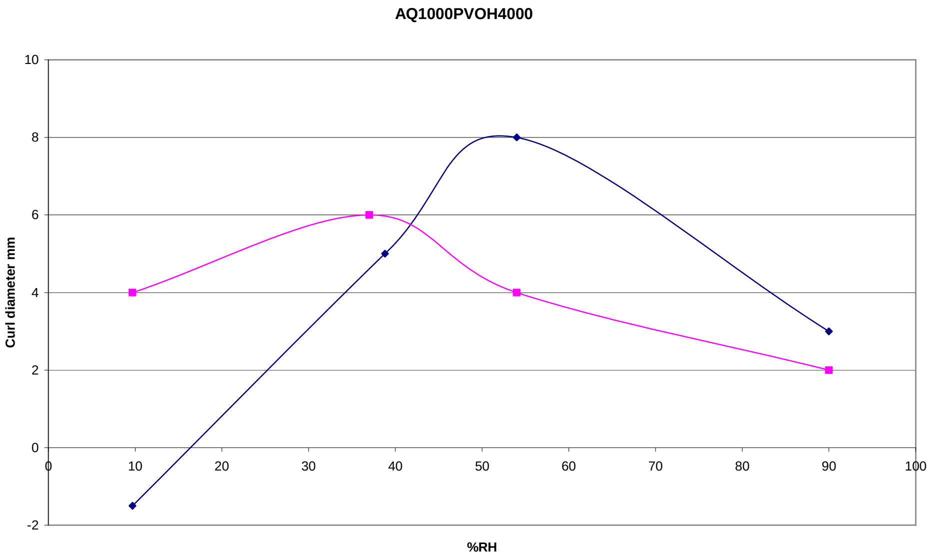


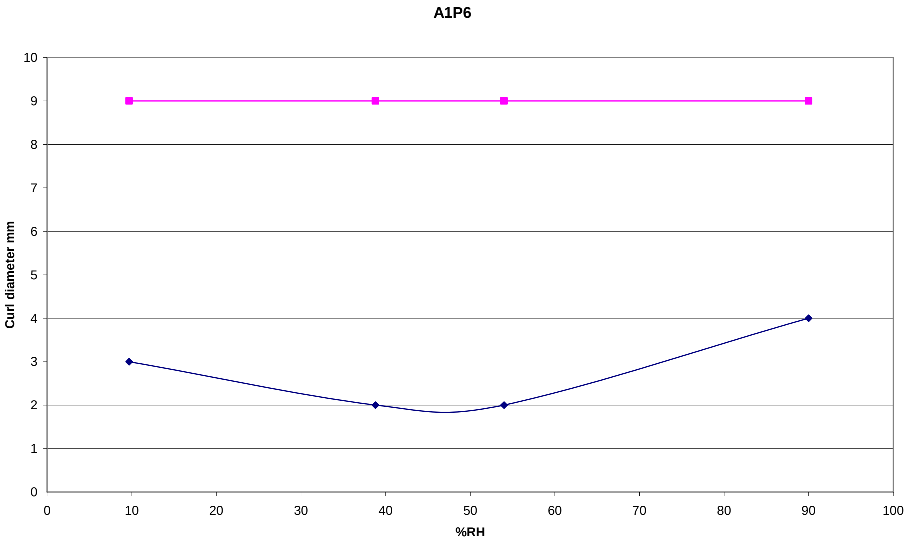
Aqualon N200 6.5% at 2000 rpm

Appendix 7: Salt solution test results

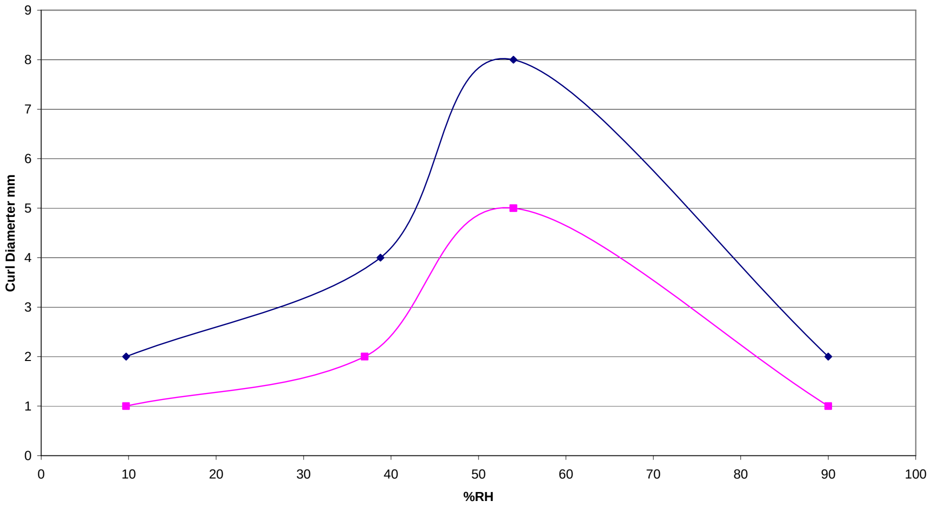




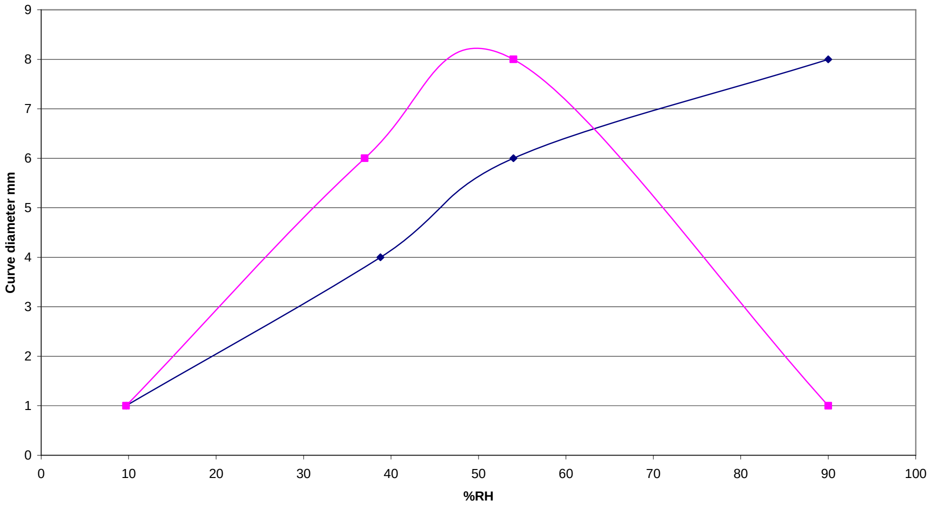

AQ1000PVOH4000
Curl diameter mm
%RH
10
8
6
4
2
0
-2
0
10
20
30
40
50
60
70
80
90
100


A1P6
Curl diameter mm
%RH
10
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60
70
80
90
100

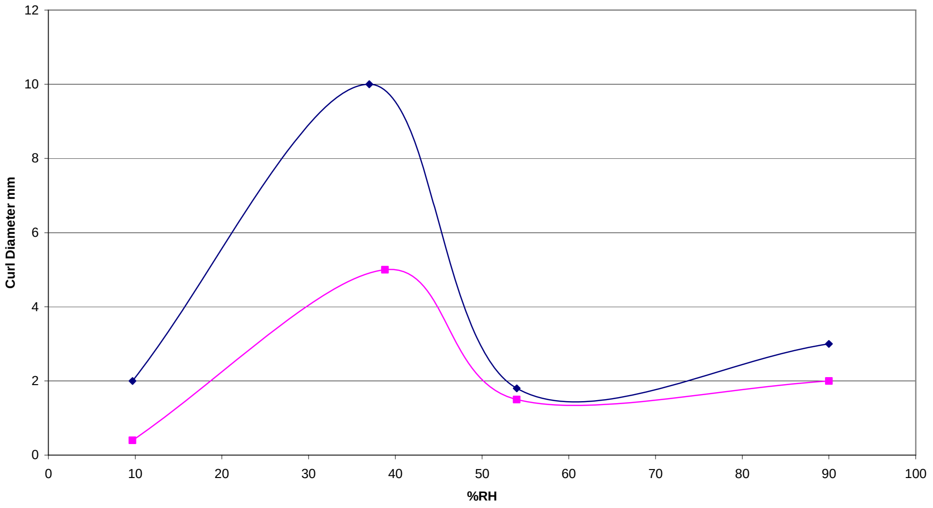
AQ2000PVOH2000

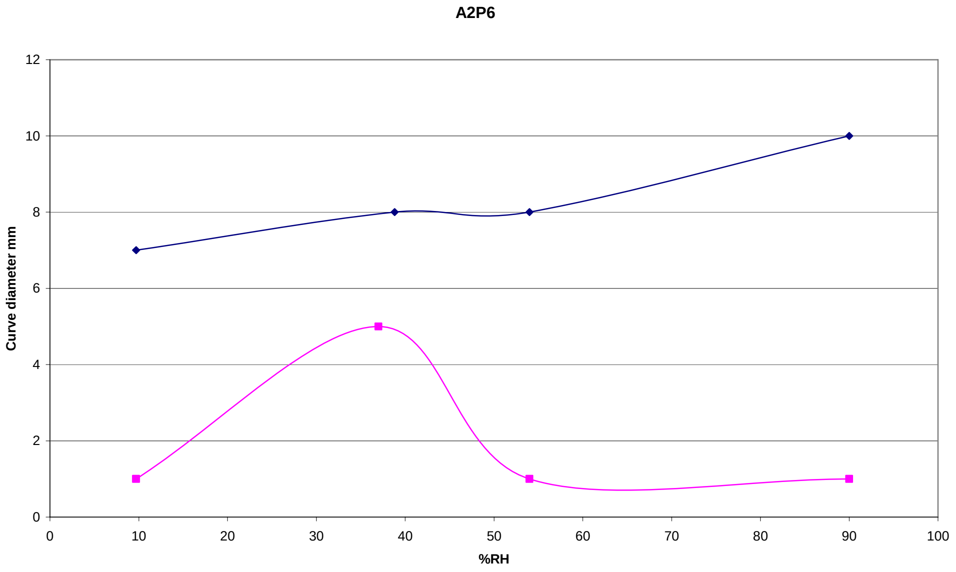


AQ2000PVOH3000



AQ2000PVOH4000




A2P6
Curve diameter mm
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
%RH